March 21, 1878.

Sir JOSEPH HOOKER, K.C.S.I., President in the Chair.

The Presents received were laid on the table and thanks ordered for them.

The following Papers were read:—

I. "Contact Theory of Voltaic Action." Parts I and II. By W. E. Ayrton and John Perry, Professors in the Imperial College of Engineering, Tokio, Japan. Communicated by Professor Sir W. Thomson, F.R.S. Received October 2, 1877.

Part I.

I.

The contact theory of voltaic action seems to have undergone no development since the date of Sir W. Thomson's experiment, which consisted in connecting a plate of zinc and a plate of copper by means of a drop of water, when it was found that the metals were brought to the same electric potential, although when metallically connected they were at different potentials. He believed that any electrolyte would behave in exactly the same way as the water of his experiment, equalizing the potentials of any two metals connected by it. The electromotive force of a simple cell, ought, in accordance with the theory, to be equal to the difference of potentials between zinc and copper in contact. A test founded on this deduction was very difficult to apply, because there was no exact determination of the difference of potential of zinc and copper in contact, Sir W. Thomson, in his experiment, having really measured the difference of potential between air at the surface of a zinc plate, and air at the surface of a copper plate. In the absence of this test, the equality of the electromotive forces of simple cells in which zinc and copper are the metals (the liquids being water, dilute sulphuric acid, and sulphate of zinc) was held as a proof of the theory. Now it is known that when two pieces of the same metal are dipped into any two liquids, which are diffusing into one another, a difference of potentials is established between the metals, and the electromotive force of a cell of this kind can in no way depend on a difference of potentials due to metallic contact. So that although in such a cell there is an action which is somewhat the same as the action in a simple voltaic cell, the theory took no account of it whatever. In fact, the explanation of voltaic action given in the latest

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treatises on electricity is felt to be incomplete, even by the writers of such treatises, and the present investigation has been entered upon in consequence.

Sir W. Thomson's result, and our own experiments lead us to imagine that when zinc and copper are immersed in water there are three successive states to be noticed:—At the instant of immersion the zinc and copper may be reduced to the same potential, so that the electromotive force of the voltaic cell E is equal to the difference of potential $\overline{ZC}$ between zinc and copper in contact; the zinc now becomes negative to the copper, so that E reaches a limit which is greater than $\overline{ZC}$; lastly, if a current passes, polarization occurs and the zinc becomes gradually less negative to the copper, E diminishing, therefore, from its maximum value. But when a saturated solution of zinc sulphate is employed instead of water, the first state, if it exists at all, exists for so short a time that practically, zinc and copper in zinc sulphate are never at the same potential. Thus (see Table X) when care is taken to keep the zinc and copper in a water cell well insulated from one another, E is found to increase from a value very little greater than $\overline{ZC}$, the electromotive force of contact of zinc and copper, to a limit, but in a zinc sulphate cell no such great increase is observed.

In our present experiments we are not concerned with instantaneous electromotive forces of contact, a short time elapsing in every case between the contact and the determination of its electromotive force; and with polarization in the ordinary sense we have equally no concern. In fact, our experiments relate to the maximum electromotive forces of simple and compound cells.

We find that zinc and copper connected by the electrolyte zinc sulphate, dilute sulphuric acid, or water are not at the same potential, the zinc being negative to the copper. In the case of dilute sulphuric acid, where polarization cannot be prevented, the negative charge of the zinc rapidly diminishes so that there is an instant at which the metals are reduced to the same potential; from Sir W. Thomson's result we may suppose that there are two such instants.

We did not measure the potentials of the surfaces which we mention but really of air in the neighbourhood of these surfaces, but the discrepancies of our results are sufficiently small for us to neglect whatever difference of potential may exist between a metallic or liquid surface, and the air in contact with it. In fact we have good reason to believe that there is no great difference of potential between a metallic or liquid surface, and the air in contact with it.

Our experiments show, but not with as much accuracy as might be desired, that the electromotive force of contact of two metals or two electrolytes, or of a metal and an electrolyte is in each case a constant; that is to say, if $\overline{AB}$ means the electromotive force of contact of the

metal or electrolyte A, and the metal or electrolyte B (measured when A and B are not in contact with other conducting substances), $\overline{AB}$ being identical with $-\overline{BA}$; then the total electromotive force of any closed heterogeneous circuit composed of the substances A, B, C, N is:—

$$\overline{AB}+\overline{BC}+ \&c. +\overline{NA}.$$

The proof of this law is very important, as it is often denied without experimental data. Profesor F. Jenkin says:—"The following series of phenomena occur when metals and an electrolyte are placed in contact:—1. When a single metal is placed in contact with an electrolyte, a definite difference of potentials is produced between the liquid and the metal. If zinc be plunged in water, the zinc becomes negative, the water positive. Copper plunged in water also becomes negative,* but much less so than zinc. 2. If two metals be plunged in water (as copper and zinc) the copper, the zinc, and the water forming a galvanic cell, all remain at one potential, and no charge of electricity is observed on any part of the system."

It will also, we think, become evident that the natures of the metals and of the electrolytes determine the electromotive force of a voltaic cell, just as the natures of the metals and the distribution of temperature determine the electromotive force of a thermo-electric arrangement, and as the nature of the two metals zinc and copper determines the electromotive force of Sir W. Thomson's mechanical cell in which copper filings fall from a copper funnel through a zinc inductor, in metallic connexion with the copper, into a copper vessel.

II.

At the surface of contact of two conducting substances there is an electromotive force of definite amount which tends to make electricity flow from one of the substances to the other. For instance, at the junction of zinc and copper there is an electromotive force of 0·75 volt which tends to cause electricity to flow from the copper to the zinc across the junction. This flow ceases when the potential of the zinc is 0·75 volt greater than that of the copper, the difference of potentials of the metals balancing the electromotive force of the junction. It is this difference of potential which is measured by the apparatus which is described below. When a substance M is said to have a higher potential than a substance N in contact with it, we mean that this state has been established in virtue of an electromotive force which exists at the junction of the substances, and that the electromotive

* We found that copper is positive to distilled water, zinc being negative to the water.

force of contact tends to produce a current of electricity from N to M across the junction.

Sir W. Thomson's method of measuring the difference of potential between two metals in contact, which consisted in hanging a needle symmetrically over two similar plates of different metals, and observing its deflexions when it was charged, first positively and then negatively, requires, in order to be accurate, all the delicacy of the arrangement and even more complicated contrivances than those employed in the quadrant-electrometer. It will be easily seen that a series of experiments for determining the difference of potentials between pairs of metals, pairs of liquids, and between liquids and metals, could only with the very greatest difficulty be carried out by a method which virtually requires the taking to pieces and refitting of a quadrant-electrometer for every experiment. The authors' attention was, therefore, directed to devising a method of investigation in which a delicate quadrant-electrometer would be employed to measure the difference of potentials between two similar metal plates themselves acted on inductively by parallel and equidistant plane surfaces of the two substances in contact, the difference of potentials between which it was desired to measure. Thus let A and B be two insulated brass plates connected with the electrodes of the electrometer. Let C under A and D under B be the surfaces whose difference of potential is to be measured. A and B are both put to earth and then insulated. C and D are made to change places with one another, C now being under B and D under A. The deflection of the electrometer needle will now give a measure of the difference of potential between C and D.*

The apparatus, by means of which our idea has been carried out, has, by a process of natural selection, assumed the form shown in the accompanying drawing. (Plate 7.) The circular brass plates A and B, 20·4 centims. in diameter, are supported and kept insulated by means of artificially dried glass stems. The leaden cups J, containing pumice stone moistened with sulphuric acid, slide in H by a bayonet-joint, and may be lowered by the handles I so as to rest on the brass plates when the instrument is not in use; thus preventing access to H of the external air.

The permanent adjustment for coincidence of the plane surfaces of the brass plates is effected by means of three wood-screws in each of the brass caps K; temporary adjustment for horizontality of the brass plates is effected by means of a spirit level and three levelling screws

* Suppose C and D to be very large, and that the protecting covering of the apparatus is far away from the insulated plates. Let the coefficients of induction of the two sets of quadrants when there is a difference of potential d between them be $s+dm$ and $s-dm$. We know from the position and shape of the needle that this is approximately true. Let a be the area of each of the insulated brass plates A and B; t the distance from A to C or from B to D. Let α be the potential of the sur-

TT, which support the wooden frame WPW', and the positions of which on the three wooden blocks T' are fixed by "hole, slot, and plane." One of these levelling screws has been removed in the drawing to show the lifting arrangement.

F and G are strips of brass soldered to the plates A and B, and connected by means of clips to wires leading to the insulated electrodes of the quadrant electrometer, and to the insulated screws A', B', of the short-circuit key.

In the drawing we have chosen to arrange the apparatus for determining the electromotive force of contact between a metal D and a liquid C. VS is a screw-jack which enables the oblong wooden table $OS'O'$ to be raised to any level, and the table may be turned round horizontally at any level. Three levelling screws, working in nuts in the table, support the metal plate D, and three others, exactly similar, support the porcelain vessel G which contains the liquid, so that the upper surfaces of both C and D are in the same horizontal plane. A binding screw a is soldered to the plate; in the present case it holds the metal strip E, which makes contact with the liquid; E must have been cut from the same sheet as the plate D. When there are two

face C, and $\alpha+v$ the potential of D at the beginning of the experiment. When A and B are connected to earth, the charge on A and its electrometer-quadrants is

$$-\frac{a\alpha}{4\pi t}-s\mathrm{V}$$

V being the potential of the needle. The charge on B and its quadrants is

$$-\frac{a(d+v)}{4\pi t}-s\mathrm{V}$$

After reversal, if C has a potential γ and D, therefore a potential $\gamma+v$, the charge on A and its quadrants is

$$\frac{a(\mathrm{V_A}-v-\gamma)}{4\pi t}+\{s-m(\mathrm{V_A}-\mathrm{V_B})\}(\mathrm{V_A}-\mathrm{V})$$

And the charge on B and its quadrants is

$$\frac{a(\mathrm{V_B}-\gamma)}{4\pi t}+\{s+m(\mathrm{V_A}-\mathrm{V_B})\}(\mathrm{V_B}-\mathrm{V})$$

where $\mathrm{V_A}$ and $\mathrm{V_B}$ are the potentials of A and B respectively. Equating the respective charges before and after reversal, and subtracting, we get

$$(\mathrm{V_A}-\mathrm{V_B})\left(\frac{a}{4\pi t}+s\right)-m(\mathrm{V_A}^2-\mathrm{V_B}^2)=\frac{2av}{4\pi t} \quad . \quad . \quad . \quad (1)$$

If we might neglect the change of capacity of the quadrants, we should have

$$v=\frac{(\mathrm{V_A}-\mathrm{V_B})\left(\frac{a}{4\pi t}+s\right)}{\frac{2a}{4\pi t}} \quad . \quad . \quad . \quad . \quad (2)$$

so that v varies as $(\mathrm{V_A}-\mathrm{V_B})$.

Now our experiments show this to be the case, and consequently (2) gives the correct value of v.

vessels of liquid, contact is made between the liquids by wetting a piece of cotton wick in one of the liquids and allowing its ends to dip below the liquid surfaces.

The brass rods N', insulated where they pass through the wooden frame by glass tubes and bone washers, are gauges which may be lowered or raised until their ends are at fixed distances below the level of the plates A and B. By the reflections of these ends at the surfaces of the liquids or plates, we can judge of the position of the level surfaces C and D. The wooden pegs O and O', and a vertical slot in the stand at $W''W'''$, enable a reversal of C and D to be made with accuracy and rapidity.

The parts of the frame $W'W''W'''$ in view of the brass plates are covered with tin plates or tin foil, connected with the outside of the electrometer. A tin plate door, of which the hinges are seen at MM, shuts up a metal box enclosing the whole apparatus, including the electrometer, short-circuit key, and connecting wires. This box is permanently in connexion with the outside of the electrometer. The plug Z of the short-circuit key is kept connected with this cover through a hole in which it may be withdrawn from its bed to insulate the plates.

We shall now describe a complete operation, to obtain the electromotive force of contact between a metal and a liquid, for example. Suppose the permanent adjustments to have been made, and that the plates A and B are quite bright. The plate D is cleaned and laid on the levelling screws R; the porcelain dish containing the liquid is laid on the levelling screws Q. By turning S and the levelling screws (O moving in its slot), and by the use of a gauge gh of which the h part represents the distance apart determined upon for A and C and B and D, we get the surfaces into their proper relative positions. The brass rod N' is now lowered until its end and its reflection at the surface of D seem to meet, and it is then made fast. Before proceeding further, the insulation of the glass rods, the permanence of the zero of the electrometer, and the permanence of position of the needle when the quadrants are insulated, are ascertained. The strip E which is quite bright is now bent to dip into the liquid, and the cover M is lowered. Insulate by means of the key, and take the zero. Now, lift the cover M, lower the table and reverse C and D; raise the table until the end of N and its reflection in the surface of the liquid nearly meet; lower the cover and take a reading. Now, short-circuit the quadrants, insulate, and proceed to take a new reading. Alternate readings are on opposite sides of the zero.

We found that when slight changes occur in the dryness of the air inside the electrometer, there are changes in the zero which are probably due to slight traces of moisture remaining on the suspension fibres of the needle. It is also to be remarked that when the quadrants of the

electrometer are insulated from one another, any slight change in the charge of the instrument causes a motion of the needle.

The hand must be trained to insulate the plates from one another. After three months' practice our insulations are so perfect that there is seldom even a tremor on removing the plug, whereas in the beginning of our experiments we often had in succession ten bad attempts at insulation. A good insulation depends on the plug leaving both sides of its seat simultaneously. This key gave better results than any of the other arrangements at our disposal.

We at first thought, from considering the change of capacity in the quadrants (as the needle moved), that our measurements would be more accurate when very small. This is not the case, but it led us to try a method of observation which may suggest itself. We brought the spot of light to zero in every experiment by acting inductively on the insulated plates A and B by means of small plates placed over them charged to a measurable difference of potential. We may employ this method modified at some future time.

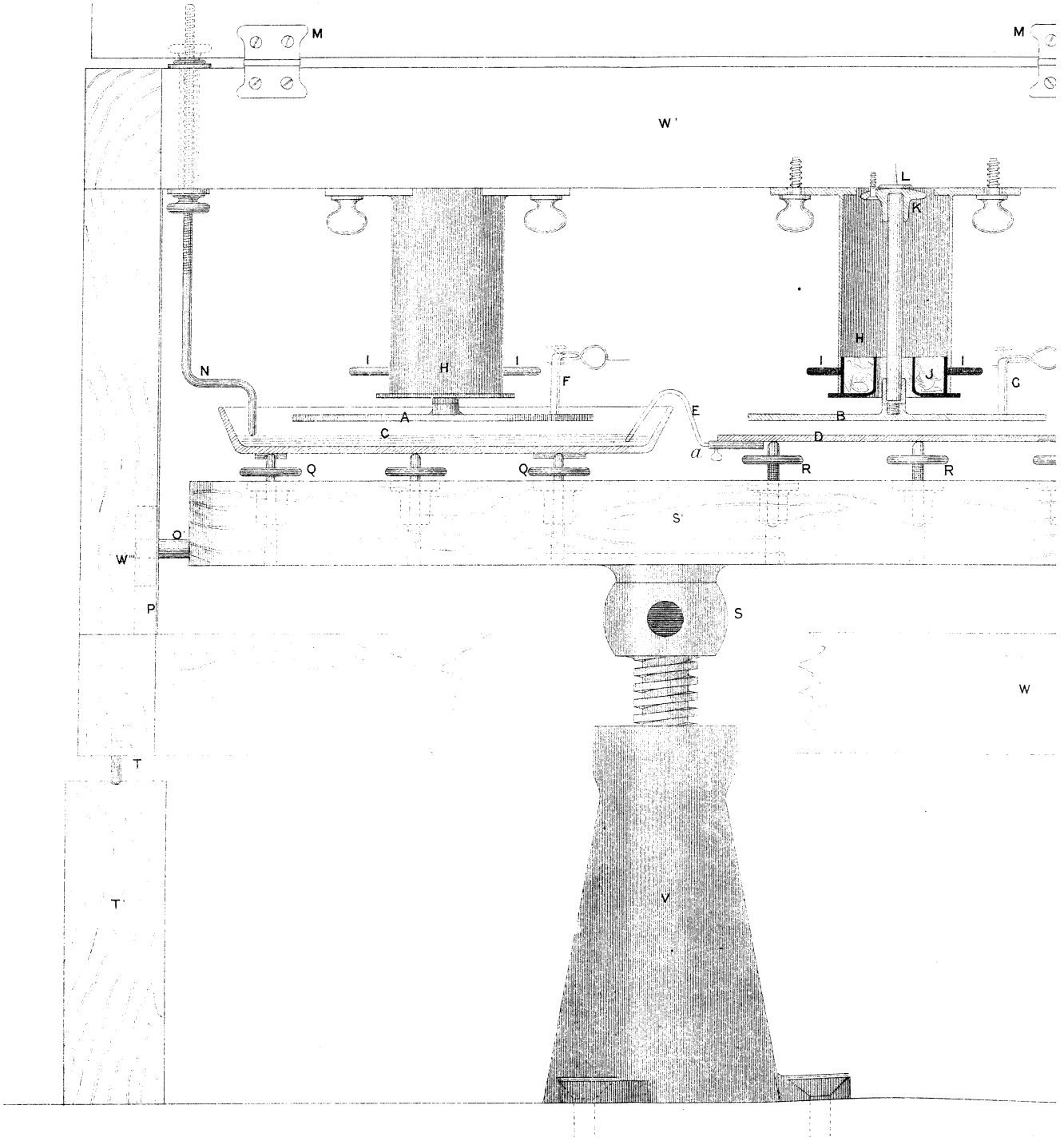
The suspension fibres of the needle were tolerably near one another, and the trap-door gauge was adjusted for as great a charge as it was convenient to give to the jar, and as it was nearly unstable it indicated extremely small changes of charge. The relative positions of the mirror G, the lamp, lens, and scale* are shown in the lower right-hand part of the Plate. The lens forms a virtual image of the wire of the lamp-slit at 60 centims. from the mirror G', and the scale I*, which is two metres from the electrometer, receives the image formed by the mirror. We had supposed that no better definition of the slit could be obtained by the use of a lens, but in reality great benefit was derived from its use, our readings being much more accurate than they would have been had the lamp-slit, without the lens, been put at 60 centims. from the mirror. We consider that our readings (as far as the electrometer itself is concerned) are fairly accurate to the one two-thousandth part of a volt.

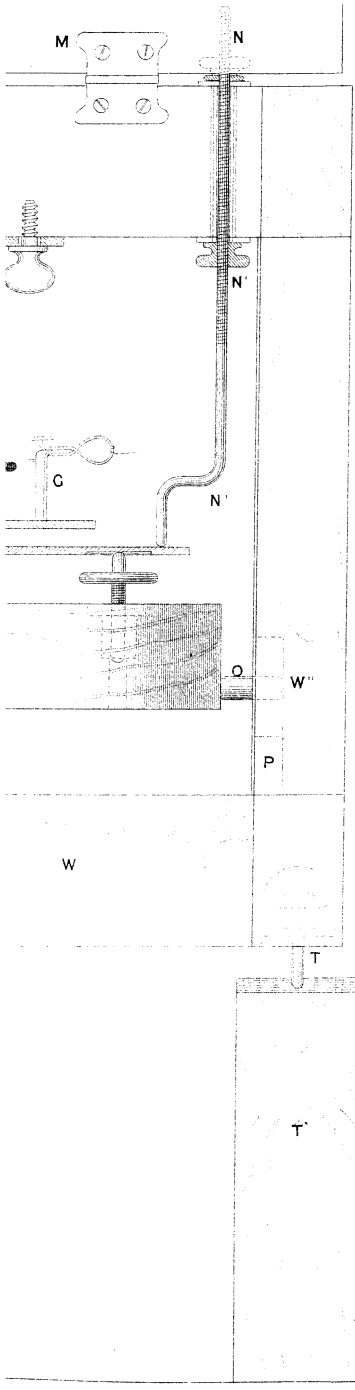
III.

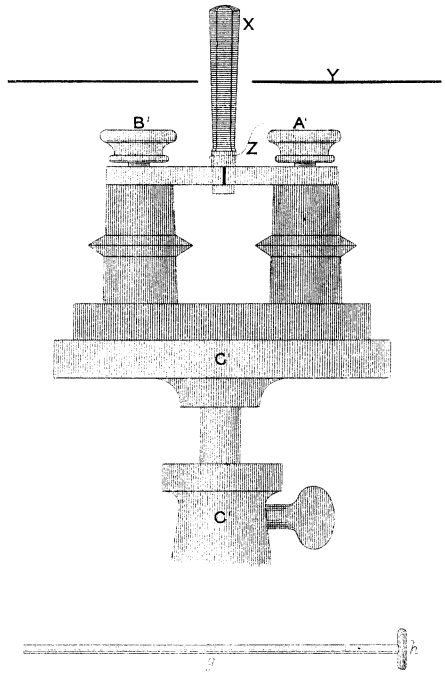
To find the relative values of deflections of the electrometer needle, two brass plates were placed under A and B at the distance of 6·4 mm. We were able to give to the plates a difference of potentials equal to the electromotive force of a Daniell, or to any fraction of this. Reversal is made by means of a key without any actual changes in the positions of the plates.

* Not represented in the Plate.

Ayrton & Perry.







ONE FOURTH (FOR FIGURE BELOW
ONE EIGHTH) OF FULL SIZE.

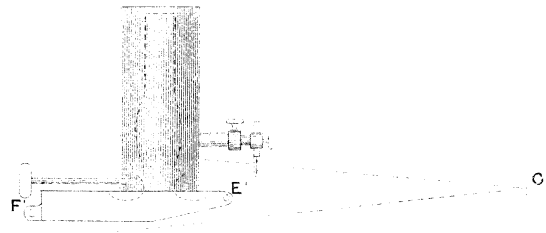


TABLE I.—9th March, 1876. Plates 6·4 mm. apart.

One Cell.

Zero.	Reading.	Deflection.
1058·0	1127·3	69·3
56·9	990·0	66·9
59·9	1129·8	69·9
64·0	997·0	67·0
65·0	1134·0	69·0
67·1	1000·0	67·1
68·0	1136·6	68·6
68·4	1000·0	68·4
68·6	1137·0	68·4
69·2	1001·5	67·7

Mean.....68·2

0·9 of a Cell.

1074·0	1138·0	64·0
73·0	1016·0	57·0
72·0	1135·0	63·0
71·0	1011·1	59·9
68·9	1129·8	60·9
67·1	1004·9	62·2
64·0	1125·0	61·0
62·8	1001·0	61·8
61·2	1122·5	61·3
60·1	998·5	61·6
59·6	1120·0	60·4
60·0	1000·0	60·0
60·0	1121·0	61·0

Mean.....61·1

0·8 of a Cell.

1063·5	1007·5	56·0
64·1	1119·1	55·0
65·2	1010·0	57·2
65·8	1121·0	55·2
67·0	1012·2	54·8
67·5	1123·2	55·7

Mean.....55·3

0·7 of a Cell.

Zero.	Reading.	Deflection.
1070·0	1022·0	48·0
70·1	1119·0	48·9
71·1	1024·0	47·1
72·0	1121·5	49·5
73·0	1025·0	48·0
73·0	1121·5	48·5
73·8	1025·0	48·8
73·5	1122·0	48·5

Mean..... 48·4

0·5 of a Cell.

1073·0	1039·0	34·0
73·0	1107·2	34·2
73·0	1038·1	34·9
72·8	1107·5	34·7
72·3	1038·0	34·3

Mean..... 34·4

0·4 of a Cell.

1068·9	1096·0	27·1
68·0	37·0	31·0
67·1	94·1	27·0
67·0	38·2	28·8
66·8	94·0	27·2
66·3	38·5	27·8
66·0	92·5	26·5
66·0	37·1	28·9
65·6	92·0	26·4
65·8	37·5	28·3

Mean..... 27·9

0·3 of a Cell.

1066·1	1086·4	20·3
66·1	45·0	21·1
66·1	86·0	19·9
66·1	45·0	21·1
66·9	87·0	20·1
67·0	45·5	21·5
66·3	86·0	19·7
68·1	46·0	22·1

Mean..... 20·7

0·2 of a Cell.

Zero.	Reading.	Deflection.
1069·0	1082·2	13·2
69·0	54·1	14·9
68·0	81·0	13·0
67·2	52·5	14·7
66·6	80·0	13·4
66·8	52·0	14·8

Mean..... 14·0

0·1 of a Cell.

1063·0	1056·0	7·0
64·0	70·6	6·5
65·0	57·8	7·2
65·5	71·6	6·1
64·8	56·5	8·3
63·4	69·1	5·7

Mean..... 6·8

Taking fractions 0·1, 0·2, &c., of 68·2, which is the mean deflection representing the electromotive force of a whole cell, we get the numbers A of Table II. The numbers B are the means of Table I.

TABLE II.

A.. 6·8	13·6	20·5	27·3	34·1	47·7	54·6	61·4	68·2
B.. 6·8	14·3	20·7	27·9	34·4	48·4	55·3	61·1	68·2

Thus the deflections are proportional to the differences of potential between the lower plates, a result which could not have been anticipated. At the distance of 16 mm., the results given in Table III were obtained, and here again we find that the deflections are proportional to the difference of potential between the lower plates.

TABLE III.—9th March, 1876. Plates 16 mm. apart.

One Cell.

Zero.	Reading.	Deflection.
1065·1	1093·0	27·9
61·8	23·5	38·3
59·5	91·5	32·0
60·6	26·5	34·1
61·3	96·0	34·7

Zero.	Reading.	Deflection.
1062 ·8	1027 ·8	35 ·0
62 ·2	94 ·1	31 ·9
64 ·9	31 ·5	33 ·4
64 ·7	98 ·0	33 ·3
62 ·1	24 ·5	37 ·6

Mean.....33 ·8

0 ·5 of a Cell.

1064 ·0	1080 ·1	16 ·1
64 ·6	45 ·8	18 ·8
57 ·1	70 ·8	13 ·7
57 ·0	37 ·5	19 ·5

Mean.....17 ·0

It was not necessary to prove the law of proportionality for other distances than 6·4 and 16 mm.

TABLE IV.—9th March, 1876. Plates 10 ·9 mm. apart.

One Cell.

Zero.	Reading.	Deflection.
1055 ·5	1101 ·5	46 ·0
57 ·0	1006 ·6	50 ·4
55 ·8	1100 ·6	44 ·8
56 ·2	1005 ·5	50 ·7
56 ·1	1100 ·0	43 ·9
55 ·0	1002 ·0	53 ·0
53 ·4	1098 ·5	45 ·1
54 ·0	1004 ·0	50 ·0

Mean.....48 ·0

The Daniell was occasionally connected with the electrometer directly. It constantly gave the deflection 230·4. It was not a new Daniell. Thus the ratio between the deflections obtained by two methods of measuring a difference of potential, one by direct connexion with electrometer, and the other by reversing the induction plates, is 3·4, when the distance between the plates is 6·4 mm., 4·8 for 10·9 mm., and 6·8 for 16·0 mm. Plotting three points on squared paper with these numbers as co-ordinates, and drawing the arc of a circle through them, we found the approximate values of the ratios corresponding with different distances given in Table V. This table was

useful in showing how any error in adjusting the plates affected the deflection.

TABLE V.

Distance in millimetres	6	7	8	9	10	11	12	13	14
Ratio.....	3·30	3·55	3·84	4·13	4·48	4·83	5·21	5·62	6·05

In subsequent experiments we used the distances 10·9 and 10·0 mm. As the electrometer was twice taken to pieces, its quadrants being altered in position, we took great care in the later experiments to determine the value of our deflections in each case.

TABLE VI.—12th March, 1876. Plates 10·9 mm. apart.

Zinc and copper metallically connected. Zinc positive to copper.

Zero.	Reading.	Deflection.
1097·1	1133·1	36·0
85·5	1048·0	37·5
77·1	1112·0	34·9
80·0	1040·6	39·4
82·1	1119·1	37·0
86·8	1047·0	39·8
83·0	1114·4	31·4
86·3	1046·0	40·3
91·2	1123·0	31·8
90·0	1047·1	42·9

Mean.....37·1

Zinc and copper connected by an acid solution of zinc sulphate at 10° C. Zinc negative to the copper.

Zero.	Reading.	Deflection.
1034·8	1026·1	8·7
34·1	41·8	7·7
36·9	30·1	6·8
37·1	49·1	12·0
39·7	31·1	8·6
40·0	51·5	11·5
45·0	35·1	9·9
43·0	55·1	12·1
43·0	35·0	8·0
42·3	52·1	9·8

Mean.....9·5

Zinc and copper connected by distilled water at 10° C. Zinc negative to copper.

Zero.	Reading.	Deflection.
1040	1033 ·1	6 ·9
40	49 ·0	9 ·0
39 ·9	32 ·1	7 ·8
39 ·8	47 ·2	7 ·4
39 ·3	32 ·1	7 ·2
39 ·2	50 ·0	10 ·8
40 ·8	32 ·9	7 ·9
40 ·2	50 ·1	9 ·9
40 ·0	31 ·2	8 ·8
39 ·8	51 ·0	11 ·2
42 ·1	32 ·3	10 ·1
42 ·0	52 ·1	10 ·1

Mean ..... 8 ·9
Mean of first eight obs. ..... 8 ·4
Mean of last eight obs..... 9 ·5

The same after two hours without zinc being cleaned.

Zero.	Reading.	Deflection.
1037 ·0	1027 ·0	10 ·0
37 ·0	48 ·1	11 ·1
37 ·0	25 ·2	11 ·8
36 ·9	47 ·6	10 ·7
35 ·8	25 ·0	10 ·8
35 ·0	46 ·4	11 ·4

Mean..... 11 ·0

Zinc and copper connected by distilled water at 45° C. cooling during experiment to 20° C. Zinc negative to copper.

Zero.	Reading.	Deflection.
1037 ·2	1054 ·0	16 ·8
37 ·1	21 ·5	15 ·6
37 ·1	51 ·2	14 ·1
37 ·1	22 ·8	14 ·3
37 ·2	49 ·2	12 ·0
..	..	..
37 ·0	54 ·0	17 ·0
36 ·8	20 ·2	16 ·6
35 ·2	51 ·0	15 ·8

Mean..... 15 ·3

In the experiments of Table VI the liquids were contained in small flat vessels which were placed below the metal plates near the middle

of the table, strips of copper and zinc dipping into the vessel from the binding screws; these strips may have been of slightly different material from the plates, that is, we are not quite certain that they were cut from the same sheets. In all subsequent experiments, the strips of metal in contact with the liquids were cut from the plates themselves.

TABLE VII.—13th March, 1876. Plates 10 mm. apart.

Zinc and copper plates connected by the acid solution of zinc sulphate of Table VI at 17° C. Zinc negative to copper.

Zero.	Reading.	Deflection.
1068·0	1085·9	17·9
68·4	62·8	5·6
65·8	74·8	9·0
66·1	58·5	7·6
67·1	55·2	11·9
67·1	72·0	4·9
	Cleaned the zinc strip.	
63·0	50·0	13·0
61·5	70·0	8·5
61·1	48·5	12·6
62·0	71·0	9·0
63·3	53·0	10·3
64·8	72·6	7·8

Mean.....9·8

Zinc and copper plates connected by dilute sulphuric acid. Zinc negative to copper.

Zero.	Reading.	Deflection.
1069·5	1057·1	12·4
68·8	76·4	7·6
68·2	62·0	6·2
68·0	73·9	5·9
68·2	62·2	6·0
68·0	73·2	5·2
67·0	61·9	5·1
66·2	68·9	2·7
	Cleaned the zinc strip.	
61·3	51·0	10·3
62·1	70·1	8·0
63·0	55·0	8·0
63·4	68·0	4·6
63·0	56·0	7·0
62·2	67·3	5·1

The mean deflection for zinc and copper contact at 10° C. being 37·1.

It is to be observed that although there was a motion of the electrometer needle when the quadrants were insulated (shown by the great difference between every two successive readings), still the observations are sufficiently consistent, and when taken two by two they show that polarization has the effect of decreasing the readings. Taking the means of every two successive readings we have in the zinc sulphate, 11·75, 8·3, 8·4, and again, after the zinc is cleaned, 10·75, 10·8, 9·0. In the acid this effect is even more marked, the deflections diminishing rapidly from 10·0 to 3·9, and again from 9·15 to 6·0. Thus we see that polarization in the ordinary sense, so far from producing a difference of potentials between zinc and copper joined by a liquid, in reality tends to reduce the difference of potentials that already existed between them.

The electrometer now began to show the existence of two faults, imperfect contact between the electrodes and the quadrants, and a slight discharge from the needle to the quadrants. The instrument was, therefore, taken to pieces, and the first fault rectified by the addition of contact springs (in addition to the little weights previously employed) between the electrodes and quadrants, and the second by the needle and quadrants being cleaned.

In observations made during the last four months on the constancy of electromotive force of cells, we found that Latimer Clark's cell when tested by an electrometer (kept in a perfectly constant state) altered very little when its poles were kept insulated. The electromotive force of this cell is known to be 1·457 volts, and we have used it as a standard to determine the changes produced in readings by changes in the positions of the quadrants.

When we compared the electromotive force of contact of zinc and copper with the constant cell, it was found in every case to be 0·75 volt at the temperature of 17° C. The deflections in the last two tables might be reduced to volts if we knew the contact electromotive force of zinc and copper at 10° C.

TABLE VIII.—13th April, 1876. Plates 10 mm. apart.

Latimer Clark's Cell.

Zero.	Reading.	Deflection.
955 ·0	892 ·0	63 ·0
954 ·5	1018 ·5	64 ·0
954 ·5	891 ·8	62 ·7
953 ·1	1017 ·1	64 ·0

Mean..... 63 ·4

Assumed to be 1 ·457 volts.

Direct reading is 355

Therefore *ratio* is $\frac{355}{63 \cdot 4}$ or 5 ·6.

Zinc and copper connected by distilled water at 17° C. Zinc is negative to copper.

Zero.	Reading.	Deflection.
953	960 ·2	7 ·2
952	947 ·0	5 ·0
952	960 ·0	8 ·0
952	946 ·5	5 ·5
951 ·9	961 ·0	9 ·1
952	945 ·0	7 ·0
952	961 ·0	9 ·0
952 ·9	946 ·2	6 ·7
	An interval of 15 minutes.	
953	961 ·0	8 ·0
952 ·8	945 ·1	7 ·7

Mean..... 7 ·32 or 0 ·168 volt.

Zinc and copper metallically connected. Zinc positive to copper.

Zero.	Reading.	Deflection.
953 ·0	926 ·0	27 ·0
952 ·7	990 ·0	37 ·3
951 ·0	920 ·3	30 ·7
950 ·1	985 ·1	35 ·0
950 ·0	919 ·5	30 ·5
950 ·2	984 ·6	34 ·4
951 ·0	918 ·0	33 ·0
951 ·1	985 ·2	34 ·1

Mean..... 32 ·7 or 0 ·751 volt.

Zinc and copper connected by saturated pure zinc sulphate at 17° C. Zinc negative to copper.

Zero.	Reading.	Deflection.
952 ·0	961 ·5	9 ·5
951 ·9	944 ·2	7 ·7
951 ·8	960 ·0	8 ·2
951 ·9	943 ·1	8 ·8
952 ·0	960 ·0	8 ·0
952 ·1	944 ·6	7 ·5

Interval of 10 minutes.

Zero.	Reading.	Deflection.
953 ·1	960 ·0	6 ·9
953 ·2	945 ·0	8 ·2
953 ·1	961 ·2	8 ·1
953 ·3	945 ·2	8 ·1
953 ·7	961 ·0	7 ·3
953 ·9	945 ·2	8 ·7

Mean of first six..... 8 ·3 or 0 ·191 volt.
Mean of last six..... 7 ·9 or 0 ·182 volt.

TABLE IX.—14th April, 1876. Plates 10 mm. apart.

Zinc and very dilute zinc sulphate (17° C.) in contact. Zinc negative to liquid.

Zero.	Reading.	Deflection.
1066 ·0	1073 ·1	7 ·1
1065 ·3	1057 ·3	8 ·3
1065 ·1	1072 ·3	7 ·2
1065 ·1	1057 ·0	8 ·1

Mean..... 7 ·7 or 0 ·177 volt.

Copper and very dilute zinc sulphate (17° C.) in contact. Copper is positive to liquid.

Zero.	Reading.	Deflection.
1060 ·0	1060 ·9	0 ·9
1060 ·0	1058 ·8	1 ·2

Mean..... 1 ·35 or 0 ·024 volt.

Slightly impure copper sulphate (at 22°·3 C.) and very dilute zinc sulphate (17° C.) in contact. Copper sulphate is positive.

Zero.	Reading.	Deflection.
1058 ·0	1055 ·8	2 ·2
1058 ·4	1061 ·7	3 ·3

Mean..... 2 ·75 or 0 ·066 volt.

Copper and slightly impure copper sulphate (27°·3 C.) in contact.

No perceptible deflection.

Dipped copper in the above copper sulphate and zinc in the zinc sulphate and connected directly with electrometer.

Deflection 246 or 1 ·010 volts.

We were subsequently rather sorry that so few observations were

made for each contact on the 14th of April; as the solutions were impure it did not at the time seem to be specially important to make the experiments with greater accuracy.

The insulated plates *A* and *B* were now cut, as they had hitherto been rather near the sides of the porcelain vessels. It was not until the 21st April that we could get a sufficiently large supply of pure saturated solutions of zinc and copper sulphates. On Friday evening, 21st April, we made our largest and most consistent series of observations. At no time since it arrived in Japan had the electrometer been in such good working order, and, therefore, we shall take the results of this evening, when possible, in preference to any others.

TABLE X.—21st April, 1876. Plates 10 mm. apart.

Latimer Clark's Cell.

Zero.	Reading.	Deflection.
1079 ·0	1019 ·5	59 ·5
72 ·1	1131 ·5	59 ·4
73 ·1	1014 ·0	59 ·1
74 ·7	1135 ·0	60 ·3
79 ·1	1020 ·6	58 ·5
83 ·5	1143 ·7	60 ·2
85 ·8	1026 ·5	59 ·3
86 ·0	1145 ·5	59 ·5
87 ·6	1028 ·3	59 ·3
86 ·7	1145 ·5	58 ·8

Mean..... 59 ·4

Assumed to be 1 ·457 volts.

Direct reading 313

Therefore ratio is $\frac{313}{59\cdot4}$ or 5 ·27.

Zinc and copper metallically connected. Zinc positive to copper.

Zero.	Reading.	Deflection.
1085 ·8	1054 ·0	31 ·8
86 ·2	1116 ·4	30 ·2
86 ·0	1054 ·6	31 ·4
85 ·8	1115 ·2	29 ·4
86 ·0	1053 ·9	32 ·1
85 ·6	1115 ·5	29 ·9
86 ·5	1056 ·5	30 ·0
87 ·2	1116 ·6	29 ·4

Mean.....30 ·52 or 0 ·749 volt.

Zinc and nearly pure saturated zinc sulphate (16° C.). Zinc negative to liquid.

Zero.	Reading.	Deflection.
1091·0	1104·7	13·7
88·6	1075·0	13·6
87·5	1100·2	12·7
86·7	1073·5	13·2
..	..	..
90·7	1075·2	15·5
91·2	1106·2	15·0
	Cleaned zinc strip.	
91·8	1075·1	16·7
91·0	1105·0	14·0
90·1	1072·1	18·0
90·3	1104·0	13·7

Mean..... 14·61 or 0·358 volt.

In the first four reversals the distance was a little too great.

Copper and nearly pure saturated zinc sulphate (16° C.). Copper negative to liquid.

Zero.	Reading.	Deflection.
1079·2	1075·2	4·0
78·2	80·2	2·0
78·7	74·5	4·2
79·2	83·2	4·9
80·5	74·8	5·7
80·0	84·5	4·5
80·0	74·1	5·9
82·0	86·0	4·0
81·8	74·6	7·2
81·2	85·8	4·6

Mean..... 4·61 or 0·113 volt.

Copper and distilled water (16° C.). Copper is positive to liquid.

Zero.	Reading.	Deflection.
1083·1	1081·0	2·1
82·8	86·0	3·2
82·9	79·6	3·3

Zero.	Reading.	Deflection.
1082 ·5	1084 ·2	1 ·7
82 ·6	79 ·2	3 ·4
82 ·2	85 ·7	3 ·5
82 ·5	78 ·9	3 ·6
83 ·2	86 ·0	2 ·8
83 ·4	79 ·8	3 ·6
83 ·9	86 ·7	2 ·8

Mean.....3 ·0 or 0 ·074 volt.

Zinc and distilled water (16° C.). Zinc negative to water.

Zero.	Reading.	Deflection.
1083 ·0	1086 ·7	3 ·7
82 ·0	75 ·2	6 ·8
82 ·8	86 ·0	3 ·2
82 ·8	77 ·9	4 ·9
82 ·6	86 ·6	4 ·0
82 ·3	75 ·1	7 ·2
81 ·6	85 ·8	4 ·2
82 ·0	75 ·5	6 ·5
82 ·0	86 ·9	4 ·9
82 ·3	76 ·2	6 ·1

Mean.....5 ·15 or 0 ·126 volt.

Copper and pure saturated copper sulphate (16° C.). Copper positive to liquid.

Zero.	Reading.	Deflection.
1085 ·0	1085 ·1	0 ·1
85 ·1	83 ·1	2 ·0
85 ·0	85 ·7	0 ·7
84 ·8	83 ·0	1 ·8
85 ·0	85 ·1	0 ·1
85 ·0	82 ·5	2 ·5
84 ·9	85 ·0	0 ·1
84 ·7	82 ·5	2 ·2
83 ·7	84 ·1	0 ·4
83 ·1	81 ·5	1 ·6

Mean.....1 ·15 or 0 ·028 volt.

Nearly pure saturated zinc sulphate and pure saturated copper sulphate. Zinc sulphate is positive.

Zero.	Reading.	Deflection.
1083·0	1080·1	2·9
81·9	82·2	0·3
82·2	80·1	2·1
81·7	82·9	1·2
82·7	80·7	2·0
82·8	83·1	0·3
82·5	80·9	1·6
83·1	83·1	0·0
82·6	80·8	1·8
82·7	83·5	0·8

Mean.....1·3 or 0·033 volt.

Distilled water and pure saturated copper sulphate (16° C.). Copper sulphate is positive.

Zero.	Reading.	Deflection.
1081·6	1077·2	4·4
82·1	84·7	2·6
82·0	78·9	3·1
82·2	84·9	2·7
83·0	80·0	3·0
83·5	86·0	2·5
84·0	80·8	3·2
83·0	85·1	2·1
82·5	79·8	2·7
82·3	84·8	2·5

Mean.....2·9 or 0·071 volt.

The sulphates and metals of Table X as a Daniell, connected directly to electrometer 1·068 to 1·081 volts, increasing very slowly.

Simple cell with above zinc sulphate, 1,000 volts. An instantaneous and constant deflection.

Simple cell with distilled water. A rapid increase in electromotive force from the instant of contact of the metals with the liquid. Our first reading was 0·832 volt, but there was a rapid increase when the reading was being taken. 0·942 was our last reading, but there was still a slow increase.

The above copper sulphate and distilled water and the metals as a Daniell. 1·060 to 1·010 volts, decreasing slowly. The same cell tried again, the metals being clean, gave 0·960 to 0·951 volt.

TABLE XI.—Some Collected Results.

	Zinc.	Copper.	Saturated pure copper sulphate.	Saturated nearly pure zinc sulphate.	Slightly impure copper sulphate.	Very dilute zinc sulphate.	Distilled water.	Ordinary water.
Zinc	..	−0·75	..	0·358	..	0·177	0·126	0·118
Copper	0·75	..	−0·028	0·113	0	−0·024	−0·074	
Saturated pure copper sulphate	..	0·028	..	0·033	..	..	−0·071	
Saturated nearly pure zinc sulphate	−0·358	−0·113	−0·033					
Slightly impure copper sulphate	..	0	..	..	..	−0·063		
Very dilute zinc sulphate	−0·177	0·024	..	..	0·063			
Distilled water	−0·126	0·074	0·071					
Ordinary water....	−0·118							

A number of results have been collected in Table XI. The numbers in a vertical column below the name of a substance are the differences of potential in volts between that substance and the substance in the same horizontal row as the number, the two substances being in contact. Thus zinc is negative to saturated pure zinc sulphate, the electromotive force of contact being 0·358 volt.

IV.

From Tables VI, VII, and VIII, we see that when zinc and copper are connected by an electrolyte the zinc becomes negative to the copper, the difference of potential seeming to be somewhat less than 0·2 volt for water, zinc sulphate, and dilute sulphuric acid. This difference of potential added to the electromotive force of contact of zinc and copper ought to be equal to the electromotive force of a simple cell.

	From Table VIII.	$\overline{ZC}$.	Sum.	Observed EMF of cell.
Pure saturated zinc sulphate.	0·191 to 0·182	0·75	0·941 to 0·932	0·907, increasing to 0·926, and still increasing slowly.
Pure water	0·168	0·75	0·918	0·832, increasing to 0·942, and still increasing slowly.

The changes which occur in the electromotive force of a cell are difficult to explain. They may be due to impurities in the metals, to air condensed at metallic surfaces, to air and other gases dissolved in the liquid, &c. They seem to be quite arbitrary, and they are often very considerable. The authors have begun an investigation regarding the causes of these peculiar effects.

The discrepancies observable in the following comparisons may also be due to the smallness of the electromotive forces of contact which were measured separately, but they are in some part due to the unexplained changes which occur in the electromotive force of a cell. Let C, Z, and L represent the copper, zinc, and liquid respectively of a simple cell; let L_1 and L_2 be the liquid in contact with the copper, and the liquid in contact with the zinc of a Daniell's cell; let $\overline{CL}$ be the electromotive force of contact of C and L, and let $\overline{CL}$ be identical with $-\overline{LC}$. Taking the five cells of Table XI, and assuming that the electromotive force of a contact of two substances as it exists in a cell is equal to its electromotive force when measured in our apparatus, we get the following results:—

	Observed EMF of Cell.
I. Daniell with pure saturated copper sulphate and nearly pure saturated zinc sulphate. $\overline{CL_1}+\overline{L_1L_2}+\overline{L_2Z}+\overline{ZC}$ $=0\cdot028-0\cdot033+0\cdot358+0\cdot750=1\cdot103$	1·068 to 1·081, increasing slowly.
II. Daniell with distilled water and pure saturated copper sulphate. $\overline{CL_1}+\overline{L_1L_2}+\overline{L_2Z}+\overline{ZC}$ $=0\cdot028+0\cdot071+0\cdot126+0\cdot750=0\cdot975$	0·995 mean from Table X.
III. Daniell with very dilute zinc sulphate and slightly impure saturated copper sulphate. $\overline{CL_1}+\overline{L_1L_2}+\overline{L_2Z}+\overline{ZC}$ $=0+0\cdot063+0\cdot177+0\cdot750=0\cdot990$	1·010 Table IX.
IV. Simple cell, nearly pure saturated zinc sulphate. $\overline{CL}+\overline{LZ}+\overline{ZC}$ $=-0\cdot113+0\cdot358+0\cdot750=0\cdot995$	1·000
V. Simple cell, distilled water. $\overline{CL}+\overline{LZ}+\overline{ZC}$ $=0\cdot074+0\cdot126+0\cdot750=0\cdot950$	0·832 to 0·942 increasing slowly.

In every case the sum of the separate contact electromotive forces is so nearly equal to the observed maximum electromotive force of the

cell, that we have good reason for believing that the electromotive force of contact of any two substances is constant whatever other substances may be in the circuit. At the same time it becomes evident that there cannot be a very great difference of potential between a metallic or liquid surface and the air in contact with it.

That the electromotive forces of a zinc sulphate cell and of a water cell are so nearly equal seems to be rather accidental. Zinc sulphate is positive to zinc and is less positive to copper, its contact electromotive forces having to be subtracted from one another; whereas water is not so positive to zinc but is negative to copper, the contact electromotive forces being therefore added together.

In any complete conducting circuit (receiving no energy from without) composed of the substances A, B,.... N, the total electromotive force is equal to $\overline{AB}+\overline{BC}+....+\overline{NA}$. Now when no changes are occurring in the circuit such as will produce a supply of energy, we know from the law of conservation of energy that this total electromotive force is nothing. In a compound metallic circuit, which is everywhere of the same temperature, this condition is satisfied. But it is not satisfied if the temperature varies in the circuit, and we find then that the total electromotive force $\overline{AB}+\overline{BC}+....\overline{NA}$ is no longer nothing, its amount depending on the nature of the metals and on the distribution of temperature. Again, we find that even when all parts of the circuit are at the same temperature, and one or more of the substances are liquid or solid electrolytic conductors, the sum of the electromotive force of contact is not nothing, its amount depending altogether on the nature of the supply of energy which exists in the circuit, and therefore on the chemical natures of the electrolytes and of the metals in contact with the electrolytes. In fact, the electromotive force of a voltaic arrangement depends on the chemical natures of the metals and of the electrolytes.

Part II.

"On a Metallic Voltaic Cell, and on Electrolytes of Great Resistance."

When any two pure insulated substances A and B are placed in contact with one another, the electromotive force of contact $\overline{AB}$ charges them to a certain difference of potentials which is numerically equal to $\overline{AB}$, and these charges of electricity represent a certain amount of energy of which the equivalent is a definite amount of chemical action. If the substances are pure there is no other electromotive force that can disturb this establishment of charge. It is probable that the chemical action which might occur at the surface of contact is very

little diminished by this charging, and we have no right to say that the total amount of possible chemical action at the contact of two metallic surfaces is simply equivalent to the energy of the charges. When A and B are solid their rigidity limits the possible amount of chemical action; but even when they are both metals if one is a liquid the total amount may be very considerable. With metals there is a limit produced by the want of mobility of the alloy, and when the liquid is not metallic there is a limit produced by the compound being insoluble, and so preventing free contact. After the charges are established the electromotive force of contact is exactly balanced, and there is no further action of any kind. If, however, A or B be a non-conductor, this establishment of charge may take a considerable time. In any case there can only be an exceedingly small amount of chemical action between any two *pure* substances, as for example, pure zinc and pure sulphuric acid.

If A, B, and C be any three substances insulated from other bodies, A and C being each in contact with B, but not in contact with each other, the electromotive forces of contact $\overline{AB}$ and $\overline{BC}$ charge the three bodies in such a way that the difference of potentials between A and B is equal and opposite to $\overline{AB}$, and the difference of potentials between B and C is equal and opposite to $\overline{BC}$. The energy required to produce this charging of the bodies is due to chemical action at the places of contact. After the three bodies are so charged there cannot be any further chemical action, and the total amount of possible chemical action at these places of contact is very little diminished by the charging.

Primâ facie we cannot compare the present difference of potentials between A and C with the electromotive force of contact that would exist between A and C were they brought together.

The establishment of the above differences of potential takes a shorter or longer time, as the bodies are more or less conducting.

If now we imagine A and C to be brought into contact, as we do not know the value of $\overline{AC}$, we cannot predict the amount of disturbance produced in the charges of A, B, and C; but we may assume that some disturbance is produced, that is, a current of electricity flows in the circuit. We can also say that after the possible chemical energy at the various junctions is exhausted, as well as the potential energy equivalent to bringing A and C in contact, then, if the temperature of the circuit is everywhere the same, there can be no further current, since there is no further supply of energy.

It is known that in a compound *solid* metallic circuit, which is everywhere at the same temperature, there is no continuous chemical action at the junctions, and consequently by the law of conservation of energy there cannot be a continuous current. Hence it has been usual

to assume that if A, B, C of our second example are metals, solid or liquid, the difference of potentials between A and C just before being brought into contact is equal to $\overline{CA}$. Now in the case of one of the metals, B, being a liquid, we have by the experiment described further on shown this assumption to be untrue; and we believe that even when the three metals are all solid, if one or more of them were rather non-conducting, and if the surfaces of contact were large, there would be obtained a result similar to that which we have obtained with solid electrolytes of high resistance. In the case of three ordinary solid metals of high conductivity, the experiment would be very difficult, if not impossible, to perform owing to the previous exhaustion of the possible chemical action through want of perfect insulation of A and C from all substances other than B before being themselves put in contact. The experiments now about to be described, as well as those given in our last paper, lead us to the conclusion that in *all cases* when A and C are brought into contact there will be a disturbance, in some cases, no doubt, only momentary, in the previous charges of A, B, and C.

A Metallic Voltaic Cell.

It may be known that when rods of zinc and copper are placed in mercury and connected with an electrometer no charge is observed. If known, this may have been regarded as a crucial test of the truth of the common theory of compound metallic circuits. Whether the zinc and copper are in contact outside the mercury or not, the amalgamation of the zinc appears to proceed at the same rate. Now, it seemed to us that in this case the impurities and great conductivity of the zinc with the great liquidity of the amalgam, and the close proximity of foreign particles to pure metal, caused the amalgamation to be produced by local action alone, so that the supply of available chemical energy for the production of a current from the zinc to copper was exceedingly small; and we have no doubt that at low enough temperatures, when the amalgam loses its liquidity, such an arrangement becomes a simple voltaic cell. It was necessary for us to use instead of zinc a metal of which the amalgam is nearly solid at ordinary temperatures. On enquiry we found that magnesium was such a metal, and on the first trial we obtained a result corroborative of the above theory.

Strips of platinum and magnesium, metallically attached to the electrodes of the electrometer, were dipped into mercury which was, perhaps, slightly impure from the presence of other metals, but which had previously been washed with distilled water, and then well dried. There was a sudden large deflection, the amount of which fluctuated very much afterwards, but which was always considerable and on the same side of the zero. On successive reversals of the electrometer

key the deflections to right and left of zero were found to be nearly equal to one another. In a short time there seemed to be an increased steadiness in the amount of deflection. When the platinum and magnesium were short-circuited for some minutes, the deflection had decidedly increased in amount on renewed insulation, and this occurred after every short-circuiting. To determine the electromotive force of the arrangement, strips of platinum and magnesium, scraped very clean, were dipped into pure mercury which had previously been washed with distilled water, and well dried. The maximum electromotive force obtained was 1·56 volts, that is about one and a half times the electromotive force of a Daniell's cell, the platinum corresponding with the copper plate in the Daniell's cell. It may be possible by mechanical or other means, or by using another metal than magnesium, to give constancy to this arrangement; and as its internal resistance is extremely small the cell may be of great practical use for the production of powerful currents. It may be remarked that as an amalgam may be easily separated into its components by distillation, such a cell by suitable arrangements can be kept in action for an indefinite time.

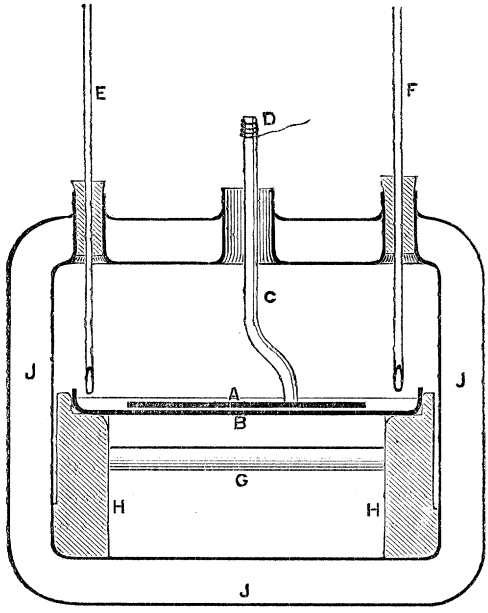
We have examined a circuit composed of the metals platinum, tin, and lead, and the coil of a galvanometer. On raising the temperature of the tin gradually we found that there was a current, and that it gradually increased. Rapid changes in the current were observable at the melting point of the tin, and there seemed to be a small electromotive force independent of thermo-electric effects. When the platinum and lead strips were connected with the electrometer, the deflections were found to be too small for decided conclusions to be drawn. We shall proceed, when time allows us, with the investigation of metallic voltaic cells.

On Electrolytes of Great Resistance.

To measure the electromotive force of the voltaic cell formed by plates of zinc and copper separated by paraffin wax and other electrolytes of great resistance, and to determine the change of conductivity of such electrolytes with temperature, we used the apparatus shown in the figure.

J is an oil-bath which may be clamped firmly to an iron stand resting on the table of such a height that D is on a level with the electrode of the electrometer. The bath was heated by means of spirit-lamps. No artificial means of cooling the bath were employed. B is a shallow dish of copper, quite plane on the bottom inner surface, and containing the electrolyte. A is a circular plate of zinc, or of copper, 12·8 centims. diameter, resting in the experiment in paraffin wax on three small pieces of glass, 0·191 centim. thick; the metal was very clean, and was quite surrounded by paraffin wax poured in in a melted state. The strip C is in one piece with the plate A, both

being cut from the same piece of metal; C is bent upwards and passes through an orifice in the bath. The wire from D to the insulated electrode of the electrometer is protected by a wide tube of metal;



this tube, the outside of the electrometer, and the uninsulated electrode being connected with B. A double door (not shown in the figure) gives access to the inside of the bath. HGH is a wooden support which may be withdrawn from the bath. E and F are thermometers of which the bulbs are near the surface of the paraffin. The difficulty of determining exactly the temperature of the paraffin wax arose from its non-conductivity; and the use of a third thermometer, passing through a tubulure horizontally underneath B, was found to add nothing to the accuracy of the temperature readings.

To obtain continuous time readings of the electrometer, we let the image of the cross fibres of our lamp slit formed by the mirror fall on a horizontal wooden roller covered with paper. This roller was 100 centims. long, and 13 centims. in diameter. A clock causes the roller to make a revolution in two minutes. We are able suddenly to change the rate of this roller to one revolution in 7·2 minutes, and we can also slightly vary the rate by altering the length of the pendulum. The image of the cross fibres is easily followed in its motion on the paper by a pencil. When the paper is cut off at any place parallel to the roller-axis it exhibits the time observations in a compact form well adapted for calculation. The clock being stopped and a scale attached

to the roller, readings may be made in the ordinary way. Such a roller and clock costs very little, and form a valuable addition to every reflecting galvanometer or electrometer.

Paraffin Wax.

The plate A being zinc and connected with the insulated electrometer-electrode, and the paraffin being solid between the two plates, we first short-circuited the arrangement to get zero, then insulated and allowed the electromotive force of the paraffin cell to charge plate A, and the electrometer quadrants in connexion with it.

A detailed account of our experiments on conductivity is given further on. It is sufficent here to state that at low temperatures the conductivity of paraffin wax is exceedingly small, the conductivity increases to the melting point, the increase being extremely rapid during melting, and there seems to be a regular increase during the melted state. Hence in the experiments with the zinc plate at low temperatures, the resistance is so great that although there is a slight charging of the quadrants due to electromotive force, this is somewhat disguised by defects of the electrometer. In fact, at low temperatures, it is impossible to measure the electromotive force of this simple cell, although the existence of an electromotive force is quite evident, but when the conductivity becomes sufficiently great, and this occurs long before there is any appearance of melting on the upper surface of the paraffin, the charge reaches a maximum with sufficient rapidity for its accurate measurement. At a few degrees above the melting point the maximum charge established itself at once, and however often the plates were short-circuited for the purpose of taking the zero, the maximum charge was found to be approximately the same, and to correspond with an electromotive force of 0·73 volt when least, and 0·75 volt when greatest: it was also not much affected by change of temperature. To make these measurements we used as a standard a Latimer Clark's constant cell.*

When the plates are charged to their maximum difference of potentials there is electric equilibrium, and no further current tends to pass through the arrangement, the electromotive force being balanced. If then E_0 represents this maximum charge, and if E_1 is the charge at a time (t_1), and E_2 the charge at the time t_2, then—

$$\frac{1}{t_2-t_1}\log\frac{E_0-E_1}{E_0-E_2}$$

multiplied by a constant depending on the electric capacity of the arrangement represents the conductivity. As the measurement of any particular temperature is rather coarse, we cannot readily compare

* In our last paper we gave 0·75 volt as the correct measurement of the electromotive force of contact of zinc and copper.

this conductivity with the conductivity for that temperature which we have otherwise determined, but we infer from the curve that the above formula gives a result twice or three times as great as the true conductivity: this, however, might have been expected from our knowledge of the phenomena of absorption in dielectrics.

Sir W. Thomson, in the "Proceedings of the Royal Society" for June 10th, 1875, describes an experiment in which plates of zinc and copper, in contact with the two sides of a plate of glass, form a voltaic cell. When the glass was sufficiently heated to become conducting there was evident charging of the plates.* In the glass cell the maximum charge became less and less after every short-circuiting, whereas in the paraffin cell the maximum charge is constant. In the one case all the elements of the circuit were solid, the glass being very far indeed from its liquefying point, so that the amount of possible chemical action at the junctions was small, and after every successive short-circuiting, there was a less and less supply until the arrangement was approaching a state which had hitherto been supposed to be peculiar to a compound metallic circuit; whereas our paraffin possessed mobility, and the amount of possible chemical action at the surfaces of contact was practically infinite in comparison with the currents charging the plates.

It is stated above that when any two pure substances otherwise insulated are brought into contact with one another, the amount of chemical action must be practically *nil*, but, as perfectly pure substances do not exist, when two bodies are brought into contact small complete circuits are formed by three or more different substances, and currents are produced until the possible chemical actions at the surfaces of contact are exhausted. Now if one or more of these substances in such elementary circuits are non-conductors, this exhaustion can only proceed very slowly, and if the substances at the surfaces of contact have immobility, the total amount of possible chemical action will be necessarily small. Hence we see that the amount of chemical action between bodies depends upon their conductivity and mobility, as well as on the electromotive forces of contact, and as the chemical action equivalent to the energy of small charges of electricity is quite incapable of being detected by the ordinary methods of chemical analysis, and as the charges are easily measurable with an electrometer, we have, if our theory be correct, in electrical measurement a method of chemical analysis which is infinitely more sensitive than any purely chemical method. Thus it is evident that in our paraffin cell there is chemical action, but our colleague, Dr. Divers, has found no traces of zinc in English paraffin oil which came out to Japan in galvanized iron cases, nor in paraffin oil heated to a temperature of 60° C., in a

* Our experiments of the increase of conductivity of glass with temperature are described in the "Proceedings of the Royal Society" for the same date.

zinc vessel for many hours. In fact in chemical analysis, something which is equivalent to current is measured by a method very much less sensitive than if the measurement were made by the best galvanometer, whereas a current which is not observable with the best galvanometer may be measured accurately with the electrometer.

It is plain that if we assume an electromotive force of contact between any two substances, there must be possible chemical action between these two substances, and this chemical action can of course only exist at the places of contact. It may proceed slowly through want of conductivity, and the amount possible in any given case may be very small because of want of mobility of either of the substances in contact, or of want of mobility of the compound formed by the action. Thus it is well known that the electromotive force of contact of glass and other substances is often very considerable, and that the chemical action between glass and most other substances is very small. This is due to want of conductivity of the glass, but when glass becomes heated, its conductivity much increases, and it then becomes capable of acting chemically on many substances. When in the melted state it is acted on chemically by the majority of substances. It is possible that this great increase of chemical activity accompanying a rise of temperature is much more due to increased conductivity than to change of electromotive force of contact. Lead glass which insulates so badly, is comparatively easily acted on by chemicals. Chemical action is always slow unless the substances are conductors, and we find that nearly all the substances which chemists find it unnecessary to dissolve before applying re-agents are conductors. In some cases previous solution may be also required for the mere purpose of producing mobility at the surfaces of contact. To expedite chemical action, solutions are stirred together; this increases the area of contact and diminishes resistance as well as rapidly bringing into contact fresh portions previously unacted on.

The alkaline earths in the solid state are very bad conductors, but when melted they are comparatively good conductors, and there is no doubt that we have here an explanation of the fact that the bottoms come out of platinum crucibles containing melted alkaline earths. We might expect that in those cases in which melted metals have a considerable electromotive force of contact, they would combine to form alloys with great rapidity, on account of their great conductivity and sufficient mobility to continue chemical combination. The great conductivity of mercury, and its mobility and the mobility of the compounds which it forms with other metals, enables it to enter rapidly into combination with those metals with which it has a great electromotive force of contact. And it is probable that the electromotive force of contact of mercury with iron or with steel is exceedingly small, or that the amalgam is a solid except at very high tem-

peratures. Cold glass is acted on by hydrofluoric acid, and this is possible on account of the great electromotive force and on account of the silicon tetrafluoride formed by the combination being volatile, and, therefore, possessing great mobility. Hitherto chemists have only employed the two ideas of chemical affinity and the amount of chemical action, but we have shown that these ideas are simplified when regarded as electromotive force of contact and currents of electricity. To connect the two ideas we have a third, viz., *resistance*, and the electrical law of Ohm becomes the chemical law—*the quantity of chemical action in unit time equals the sum of a great number of terms, each of which is an electromotive force divided by a resistance.*

Gutta-Percha.

The metallic plates of the last experiment were carefully cleaned, and the paraffin wax replaced by a sheet of gutta-percha, previously scraped, washed with soap and water, ordinary water, alcohol, sodium carbonate, and hot distilled water, and thoroughly dried. The upper plate A was of clean zinc as before. Our experiments on the conductivity of gutta-percha, described further on, show that it increases with the temperature, not only at the low temperature at which it has hitherto been examined, but also after it has become plastic at higher temperatures.

At the lowest temperature at which we examined the arrangement there was a decided charging of the plates, but it was so slow that we must regard the measurement of the minimum electromotive force 0·23 volt as being too small, for a careful examination of the defects of the electrometer showed that under these circumstances the measurement *might* be too small. At higher temperatures the maximum charge was established with much greater rapidity.

On each day, some time after the commencement of the experiment for that day, the electromotive force having remained constant for some time suddenly increased, and then remained nearly constant at its higher value. This seemed at first to be due to the plates having been short-circuited for intervals of four minutes or more, but we afterwards found that it occurred when the plates were only short-circuited for a few seconds to get to zero. Also, it did not seem to occur at a particular temperature; on one occasion the sudden rise happened at about 35° C., and on another at about 72° C. On the first of these days the mean low electromotive force was 0·584 volt, and the mean high 0·763 volt, the very lowest and very highest being 0·54 and 0·86 volt. On the second day the mean low was 0·534 volt and the mean high 0·773 volt, the lowest and highest being 0·529 and 0·789 volt. We are sure, when these measurements were made, that the conductivity of the gutta-percha was sufficiently great to eliminate any effects due to the minute defects of the electrometer.

As in the case of paraffin, the conductivity calculated from the time readings, whilst the zinc and copper plates were establishing their charge, is greater than the conductivity measured independently by two copper plates charged with a battery for about five minutes and then kept insulated.

Ebonite.

Between the zinc and copper plates was placed an ebonite sheet, having an average thickness of 0·35 millim. It was chemically clean, and there was no surface conduction at even low temperatures. We found, as in the previous cases, that there was evidence of an electromotive force, but the charging proceeded very slowly until about 36° C., when the conductivity had greatly increased. During thirty-five minutes the temperature steadily increased to 74° C., and as there was no indication of a maximum charge, we let it increase without short-circuiting during this thirty-five minutes, at the end of which time the deflection indicated an electromotive force of 3 volts. After short-circuiting the charge again established itself, but it did not increase as rapidly as it had done at first at the lower temperature, although from our independent experiments we know that the conductivity is greater at higher temperatures. Precautions have been taken to avoid any sliding of the ebonite plates during the experiments; for certain preliminary observations showed that such sliding would produce charges of electricity which would mask mere voltaic results. From the mathematical expressions for conductivity and from our experimental determinations of the conductivity at any given temperature, we endeavoured, by calculation, to discover whether the first set of time readings indicated an approach to a maximum, but we obtained inconsistent results; the maximum electromotive force thus calculated varying from 3 to 12 volts. After the experiments the zinc plate was found to be only slightly dulled in its polish and not coloured, neither did the copper plate appear much changed in appearance, but a lead weight which had been laid on the zinc to keep it in close contact with the ebonite was found to be quite red.

It is evident, therefore, that this arrangement had nothing in common with an ordinary simple cell, the great charging of the plates being due to a decomposition of the ebonite by heat.

India-Rubber.

In November, 1875, we endeavoured to find the electromotive force of a simple cell formed by placing a sheet of india-rubber containing sulphur between zinc and copper plates, and we then obtained results analogous to those which have just been described for ebonite. During the present investigation, we expected to obtain the same results, since we used the piece of india-rubber which had previously been

employed. Contrary to our expectations, however, there appeared to be no further decomposition of the india-rubber by heat, and results analogous to those previously obtained with the paraffin wax were met with. Probably, therefore, all the sulphur that could easily be liberated had been expelled by the previous heating. At about 90° C., the conductivity was sufficient to enable us to measure, with some accuracy, the electromotive force, which we found to be 0·168 volt; but somewhat as in the case of the gutta-percha, between 90° and 100° C., the electromotive force increased to 0·356 volt. This increase did not appear to be as sudden as in the case of gutta-percha, but, as before, the electromotive force was fairly constant on each side of this place of changing.

Shell-Lac.

An extremely thin sheet of shell-lac was placed between plates of zinc and copper, as in the preceding experiments. At low temperatures there was evidently an electromotive force, which, at 28° C., we were able to measure, as the conductivity was sufficiently great. From this temperature upwards there was practically no change. In fact, the electromotive force was constant and equal to 1·12 volts. At temperatures higher than 65° C., the arrangement established its charge after short-circuiting with the rapidity of an ordinary liquid voltaic cell.

Resistances of the above Electrolytes.

It has been usual for telegraph engineers to measure the resistance of gutta-percha, india-rubber, &c., after a current has been passing through the material for one or for not more than three minutes. Now, although this may be a very valuable test of a telegraph cable, since the amount of apparent loss, through want of insulation during the first small period of charge, is one of the elements affecting the received current, still since this loss is due to two causes, soaking in and true conductivity, and since the former is at first so very great compared with the latter, the real resistance can only be ascertained after the current has been on for a length of time. The practical time of charging necessary to enable the current to be a true measure of the conductivity seems to be less at higher temperatures, and in our experiments we have endeavoured to approximate to the elimination of soaking in.

Paraffin-Wax.

In November, 1875, we made a great number of time observations of the difference of potentials of two copper plates immersed in paraffin-wax, and kept asunder by three small pieces of glass, 0·191 centim. thick, the upper plate having been originally charged to a certain potential, and the lower plate kept in connexion with the earth. We

found that the conductivity increased with temperature, the increase being very rapid near the melting point, at which place, as we used no auxiliary condenser, the rate of loss of charge was very high. To measure the conductivity of melted paraffin, we employed a very delicate reflecting astatic galvanometer of 20,000 ohms resistance; one Daniell's cell, through a resistance of 120 megohms, gave a deflection of 131·3 divisions on an ordinary scale, at about a metre distance. The current from a battery having a measured electromotive force 47 times that of our standard Daniell passed through the paraffin and the galvanometer. Full precautions were taken to avoid all leakage except through the paraffin, the deflection of the galvanometer needle due to instrumental leakage alone being quite imperceptible. The thermometers did not indicate truly the temperature of the paraffin, being too high when the apparatus was heating, and too low when it was cooling; but as the cooling was very slow, the results which are given in following table obtained during cooling, and which, when plotted, give the curve JK (fig. 1, p. 231), may be regarded as being fairly correct, for the observations seem to be all very consistent with one another.

The area of the upper plate was 56·25 square centims., and hence if x is the specific resistance in megohms per cub. centim. of paraffin, and if D is the deflection on the galvanometer scale,

$$\text{Log } x = 8\cdot3374 - \log D.$$

Temperature.	D.	x in megohms.
90° ·6 C.	167 ·9	$1\cdot295\times10^{6}$
96° ·8	229 ·9	$0\cdot946\times10^{6}$
91° ·0	191 ·6	$1\cdot135\times10^{6}$
84° ·0	151 ·9	$1\cdot432\times10^{6}$
80° ·0	132 ·3	$1\cdot644\times10^{6}$
76° ·0	115 ·9	$1\cdot876\times10^{6}$
70° ·2	94 ·5	$2\cdot301\times10^{6}$
65° ·1	78 ·0	$2\cdot788\times10^{6}$
60° ·0	64 ·0	$3\cdot398\times10^{6}$
55° ·2	55 ·0	$3\cdot954\times10^{6}$
50° ·0	43 ·0	$5\cdot058\times10^{6}$

In the above table we have given only every fifth observation. The curve ML has for co-ordinates the temperature and galvanometer deflection as the temperature increased. The points M, L, K, J, correspond respectively with the temperatures 90° ·6, 94° ·7, 93° ·1, 48° C. In this and in the other curves we have employed such scales as have seemed to us most convenient. In every case we give the true co-ordinates of some points, and from these the scale may be easily determined. Ordinates measured parallel to the line OX represent temperature, the temperature increasing towards O.

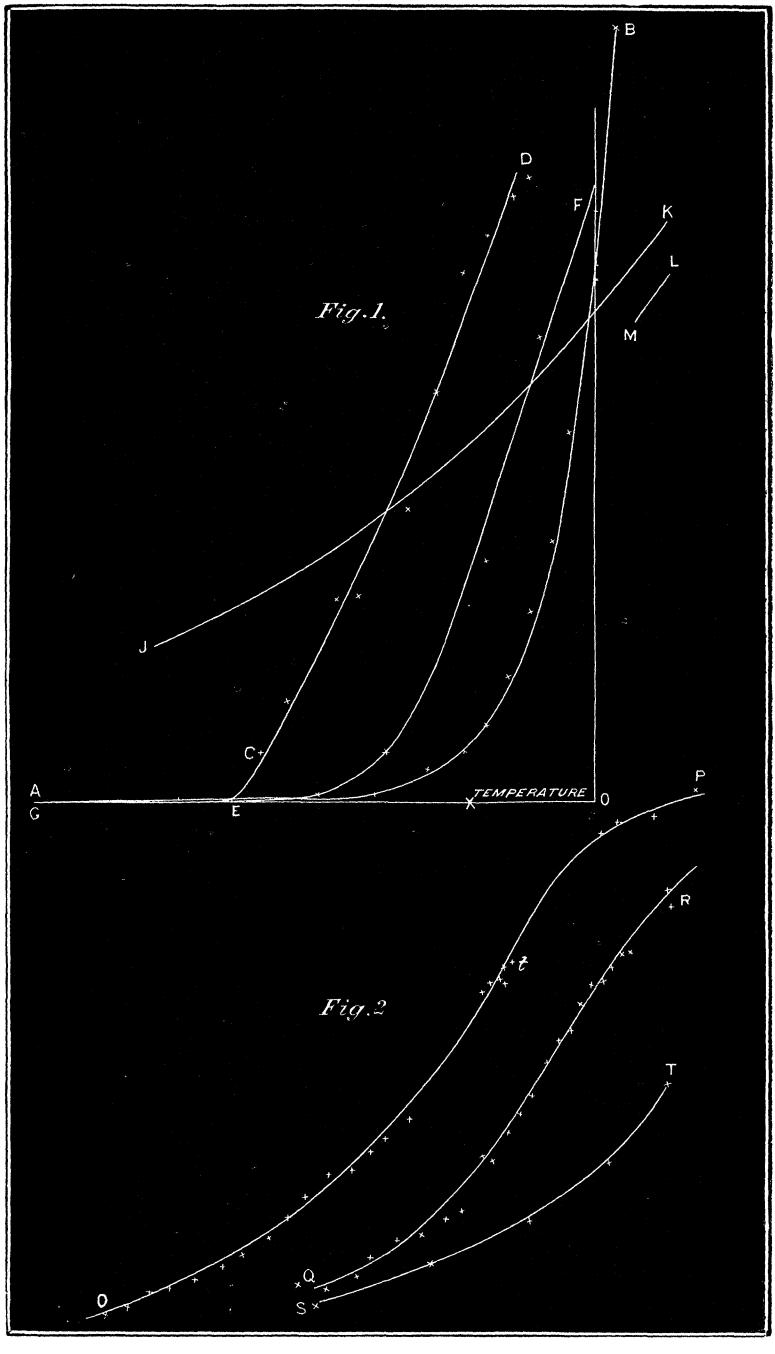


Fig. 1.

Fig. 2

We were unable to obtain galvanometer and electrometer tests at the same temperature, since the galvanometer did not give deflections at low temperatures; and as we had not at this time designed the time roller described above, and as no auxiliary condenser was used with the electrometer, the loss of charge was too rapid at high temperatures to make accurate time observations.

The oil-bath used in November, being small and otherwise inconvenient, we proceeded in May of this year with the investigation, using the apparatus described above. At low temperatures time observations of loss of charge were taken on a fixed scale. Near the melting point time observations were taken on the roller in motion, and at higher temperatures, one terminal of an auxiliary condenser of one-third microfarad capacity and excellent insulation was attached to the plate A, the other terminal of the condenser being connected with B. Four Daniell's cells were used to charge A.

At 20°·9 C., the temperature of the room, A experienced no loss of charge in ten minutes whether or not the condenser was attached.

A number of preliminary experiments showed as before that there was a great increase of conductivity at melting. For instance, on May 15th, when the temperature was rising, the paraffin appeared to be solid at 46° C., and it appeared to be liquid at 52° C., and between these two temperatures we obtained the following results, t being measured in minutes always.

Temperature.	$\frac{1}{t}\log\frac{E_1}{E_2}$	x in megohms.
46° ·5 C.	0 ·00114	34190 $\times 10^6$
48° ·3	0 ·00168	26480 $\times 10^6$
50° ·0	0 ·00225	17320 $\times 10^6$
50° ·4	0 ·00607	6421 $\times 10^6$
50° ·8	0 ·01600	2436 $\times 10^6$
51° ·15	0 ·03970	998 ·2 $\times 10^6$
51° ·2	0 ·07000	556 ·8 $\times 10^6$
51° ·3	0 ·30000	129 ·9 $\times 10^6$
51° ·35	1 ·26000	30 ·93 $\times 10^6$
	Afterwards when cooling.	
48° ·4	0 ·0689	565 ·7 $\times 10^6$
48° ·2	0 ·0308	1266 $\times 10^6$
45° ·1	0 ·0133	2930 $\times 10^6$

These results cannot be compared directly with those previously obtained with the galvanometer, because in the former case the paraffin was cooling from a high temperature, 90° C., whereas in this case the temperature was only raised to 51°, and it is well known that when paraffin is cooled from a high temperature, it will remain liquid

at temperatures at which it would be solid were it being gradually heated from a low temperature.

Curve AB, May 16th, gives the relative conductivities when the paraffin was rising from 54° C. to 56° C. At 54° the paraffin seemed to be solid, and it did not appear to be melted at its upper surface, even for some time afterwards, when the thermometers indicated 60° C. But at 56° C. it was covered with white eruptions. With the condenser, May 16th, we obtained the following tests. As we did not employ the roller the conductivities deduced from detached readings are often inconsistent, and yet each of these conductivities was deduced from a number of observations, in some cases from twenty. This shows the difficulty of making eye observations, for when using the time roller and tracing on it with a pencil the path of the image of the cross fibres, no such inconsistences were met with.

Temperature.	$\frac{1}{t}\log\frac{E_1}{E_2}$	x in megohms.
60° ·2 C.	0 ·1175	$4\cdot482\times10$
The paraffin was quite liquid over the upper plate.		
62°	0 ·0205	$2\cdot569\times10^6$
64° ·5	0 ·0222	$2\cdot372\times10^6$
68° ·5	0 ·0261	$2\cdot018\times10^6$
72° ·5	0 ·0312	$1\cdot689\times10^6$
76° ·6	0 ·0373	$1\cdot412\times10^6$
77° ·8	0 ·0389	$1\cdot354\times10^6$
77° ·4	0 ·0334	$1\cdot577\times10^6$
76° ·4	0 ·0316	$1\cdot666\times10^6$
75° ·3	0 ·0310	$1\cdot699\times10^6$
74°	0 ·0268	$1\cdot736\times10^6$
72° ·4	0 ·0246	$2\cdot141\times10^6$
70° ·7	0 ·0242	$2\cdot177\times10^6$
69° ·6	0 ·0240	$2\cdot195\times10^6$

These results may be compared with the galvanometer results, because in both cases the temperature was cooling from a point much above melting. Considering the great difficulty of measuring the temperature, the agreement of these results with the galvanometer results may be regarded as very satisfactory.

May 20th. Time roller used for the first time, quick motion only employed, that is, one revolution in two minutes. The battery was kept connected with the plates for intervals of time varying from three to ten minutes before plate A was insulated. The roller curves are in themselves extremely interesting, but we think that to give them in the present paper would be superfluous. The curve EF gives the values of $\frac{1}{t}\log\frac{E_1}{E_2}$ without condenser from 52°·6 C. to 58° C.; the co-

ordinates of the points E, a, b, c, &c. . . . F, have the values given in the following table:—

	Temperature.	$\frac{1}{t}\log\frac{E_1}{E_2}$	x in megohms.
	49° ·7 C.	0 ·0044	8857 $\times 10^6$
	51° ·2	0 ·0050	7794 $\times 10^6$
E	52° ·6	0 ·0122	3195 $\times 10^6$
a	54° ·0	0 ·0677	575 ·7 $\times 10^6$
b	54° ·65	0 ·1620	240 ·6 $\times 10^6$
c	55° ·2	0 ·3612	107 ·9 $\times 10^6$
d	57° ·0	1 ·7040	22 ·88 $\times 10^6$
F	58° ·0	3 ·2776	11 ·90 $\times 10^6$
	59°	4 ·1608	9 ·367 $\times 10^6$

Of the curve GCD, the part from G to C was obtained without using the condenser, and for the part from C to D, the condenser was employed. The co-ordinates of the points C, a, b, &c., . . . D are as follows:—

	Temperature.	$\frac{1}{t}\log\frac{E_1}{E_2}$	x in megohms.
C	59° ·8 C.	0 ·0065	8 ·104 $\times 10^6$
a	61° ·5	0 ·0096	5 ·487 $\times 10^6$
b	62° ·85	0 ·0097	5 ·430 $\times 10^6$
c	64° ·4	0 ·0126	4 ·180 $\times 10^6$
d	66° ·45	0 ·0138	3 ·187 $\times 10^6$
e	68° ·5	0 ·0193	2 ·729 $\times 10^6$
f	70° ·2	0 ·0250	2 ·107 $\times 10^6$
g	72° ·2	0 ·0267	1 ·972 $\times 10^6$
h	73° ·8	0 ·0285	1 ·848 $\times 10^6$
D	75° ·2	0 ·0293	1 ·798 $\times 10^6$

Assuming that the paraffin is always in the same state when the thermometer gives the same reading during a regular rise in temperature of the apparatus, we find,

$\frac{1}{t}\log\frac{E_1}{E_2}$ without condenser for 59° C. to be 4 ·36.

$\frac{1}{t}\log\frac{E_1}{E_2}$ with condenser for 59° C. to be 0 ·0059.

Therefore the ratio of the relative conductivities measured without and with the condenser, is about 740, and hence, assuming the specific inductive capacity of paraffin does not change much with temperature, and that the change of capacity of the pair of quadrants can be neglected, we can calculate the specific resistance in megohms of a cubic centimetre of paraffin wax from our time readings by the

following formulæ, which have been employed in obtaining the values of x given above.

Without condenser,

$$\log x = 7\cdot5908 - \log\left(\frac{1}{t}\log\frac{E_1}{E_2}\right),$$

with condenser,

$$\log x = 4\cdot7216 - \log\left(\frac{1}{t}\log\frac{E_1}{E_2}\right),$$

t being as usual measured in minutes.

The changes which occur in the conductivity of paraffin wax when it melts are best seen in the curve AB. It is probable that the curve from E to F represents the continuation of AB to a different scale, and we have found that the further continuation beyond the point F is represented by the curve from C to D, which is again drawn to a different scale.

All the loss of charge observations are combined in the curve GCD, and it is quite evident that there is a decided want of continuity in the curve. It is probable that paraffin follows the logarithmic law until it nears the melting point, but after melting the increase of conductivity would seem to be proportioned to the increase of temperature. The curve CD may be a straight line, but the galvanometer results give a curve which is decidedly concave upwards; it is still, however, a very flat curve.

Solid paraffin during the four degrees before melting alters its specific resistance per cubic centimetre from 34000×10^6 megohms to 1000×10^6 megohms. For the lowest temperature at which it can be said to be melted, its specific resistance seems to be about 10×10^6 megohms, and $77^\circ\cdot8$ C., to be pretty accurately $1\cdot354\times10^6$ megohms.

Gutta-Percha.

The effect of heat on the conductivity of gutta-percha was studied by noting the loss of charge of two copper plates separated by a sheet of gutta-percha 0·191 centim. thick. The conductivity even at ordinary temperatures was sufficiently great for the employment of a condenser. The values of $\frac{1}{t}\log\frac{E_1}{E_2}$, are shown in the curve OP (fig. 2), the co-ordinates of the points O, a, b, &c., . . . P of the curve are given in the following table. x, the specific resistance per cubic centimetre in megohms has been calculated from the formula:—

$$\log x = 4\cdot7217 - \log\left(\frac{1}{t}\log\frac{E_1}{E_2}\right).$$

The plastic condition of the gutta-percha, at the higher temperatures has indicated itself in the curve between t and P.

	Temperature.	$\frac{1}{t}\log\frac{E_1}{E_2}$	x in meghoms.
O	83° C.	0·1052	$\cdot5008\times10^6$
a	80°	0·1005	$\cdot5243\times10^6$
b	77°·4	0·0984	$\cdot5355\times10^6$
c	76°·5	0·0964	$\cdot5466\times10^6$
d	70°·7	0·0732	$\cdot7197\times10^6$
e	70°·3	0·0693	$\cdot7603\times10^6$
f	70°·2	0·0723	$\cdot7288\times10^6$
g	70°·0	0·0701	$\cdot7516\times10^6$
h	69°·5	0·0693	$\cdot7603\times10^6$
i	68°·8	0·0676	$\cdot7794\times10^6$
j	64°·4	0·0442	$1\cdot192\times10^6$
k	62°·8	0·0406	$1\cdot298\times10^6$
l	61°·9	0·0381	$1\cdot383\times10^6$
m	60°·6	0·0345	$1\cdot527\times10^6$
n	59°·0	0·0335	$1\cdot573\times10^6$
o	57°·5	0·0290	$1\cdot817\times10^6$
p	56°·4	0·0252	$2\cdot090\times10^6$
q	55°·1	0·0219	$2\cdot406\times10^6$
r	53°·4	0·0180	$2\cdot927\times10^6$
s	52°·0	0·0156	$3\cdot378\times10^6$
t	50°·1	0·0131	$4\cdot022\times10^6$
u	48°·4	0·0112	$4\cdot704\times10^6$
v	47°·0	0·0101	$5\cdot217\times10^6$
w	45°·5	0·0075	$7\cdot025\times10^6$
P	44°·0	0·0059	$8\cdot930\times10^6$

If we may assume that from P downwards in temperature the resistance of gutta-percha follows the well-known logarithmic law, we find at 24° C. the specific resistance per cubic centimetre is 83×10^6 megohms, showing that for a sheet the gutta-percha is fairly good.

Ebonite.

In determining the conductivity of ebonite, we at first proceeded as described above, using a pair of copper plates; but we found that the charge instead of decreasing through conductivity increased apparently indefinitely. On replacing the copper plates by sheets of platinum we obtained consistent results, but this may have been due to the sulphur that could easily be liberated by heat having been driven out in the previous heating. QR is the curve connecting the conductivity, or rather $\frac{1}{t}\log\frac{E_1}{E_2}$, and the temperature. This curve is nearly straight from 65° C. to 96° C., our highest temperature. No rapid change in the conductivity is anywhere perceptible.

As we could not employ the auxiliary condenser in consequence of

the resistance of the ebonite being very great, and the loss, therefore, very slow even at high temperatures, and as the specific inductive capacity of ebonite is unknown, we were compelled to make experiments to determine the electric capacity of our arrangement. This was very difficult on account of the small area, 45·6 square centims., of the ebonite in contact with the platinum. The result, therefore, which we obtained, and from which we deduced the specific inductive capacity of ebonite to be 1·7, must only be accepted as very rough, and merely of use in giving us approximate values of the resistance at various temperatures. The number 1·7 seems too small for a composition of india-rubber and sulphur. Consequently, all our calculated values of x may be too large, and ought to be reduced in the ratio of 1·7 to the true specific inductive capacity of ebonite.

	Temperature.	$\frac{1}{t}\log\frac{E_1}{E_2}$	x in megohms.
Q	36°	0 ·0027	61030×10^6
a	41°	0 ·0026	63390×10^6
b	46°	0 ·0031	53160×10^6
c	48° ·5	0 ·0038	43370×10^6
d	53°	0 ·0045	36630×10^6
e	57°	0 ·0048	34340×10^6
f	61°	0 ·0054	35020×10^6
g	64°	0 ·0057	28920×10^6
h	67°	0 ·0077	21400×10^6
i	68° ·5	0 ·0076	21690×10^6
j	71°	0 ·0086	19160×10^6
k	73°	0 ·0093	21560×10^6
l	75°	0 ·0100	16480×10^6
m	77°	0 ·0112	14720×10^6
n	79°	0 ·0120	13740×10^6
o	80° ·5	0 ·0124	13290×10^6
p	82° ·3	0 ·0133	12400×10^6
q	84°	0 ·0140	11770×10^6
r	85° ·6	0 ·0142	11610×10^6
s	87° ·0	0 ·0147	11210×10^6
t	88° ·6	0 ·0152	10840×10^6
u	90°	0 ·0153	10770×10^6
v	94° ·4	0 ·0175	9419×10^6
R	96° ·8	0 ·0170	9696×10^6

India-Rubber.

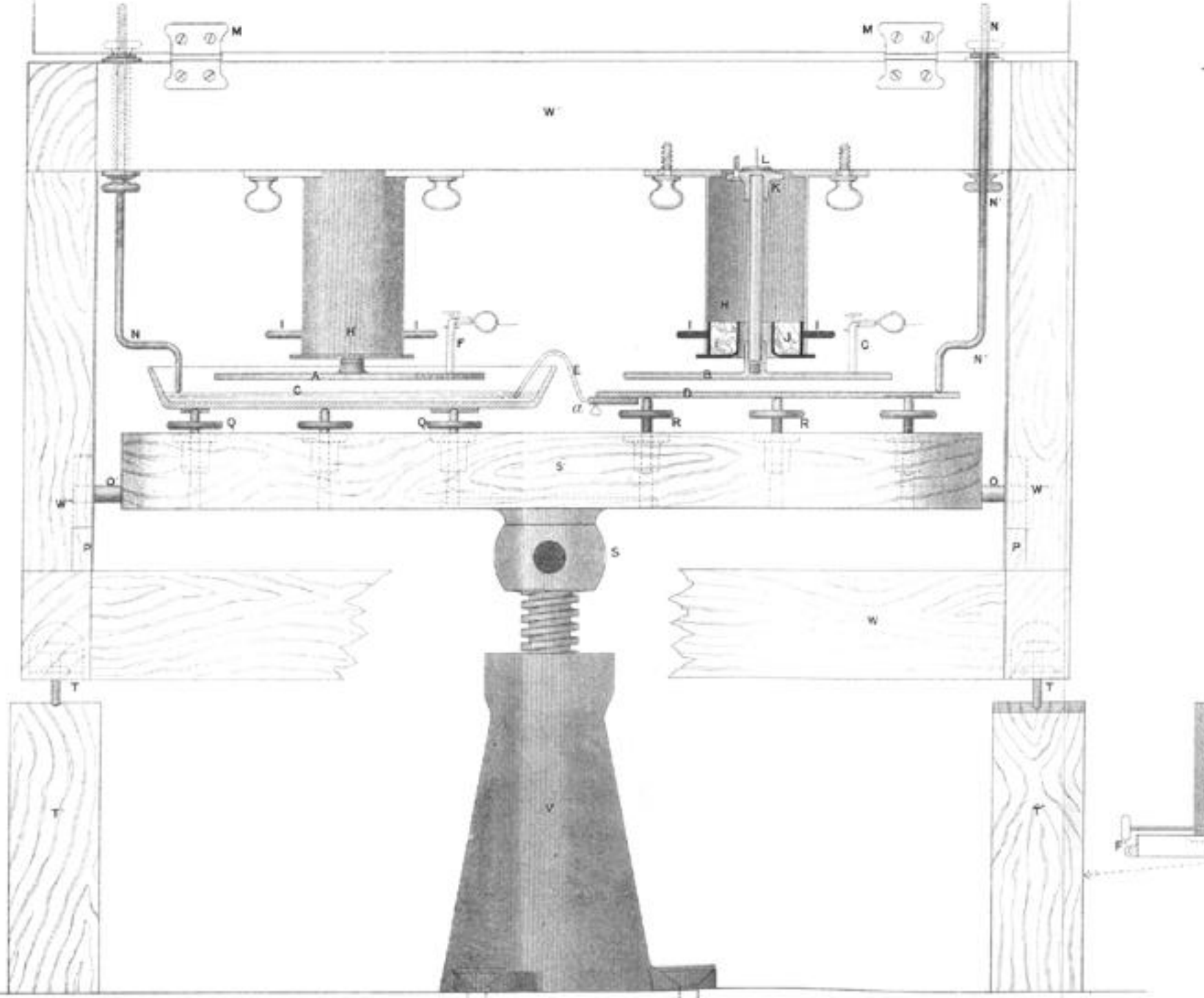
The relation of conductivity to temperature of a chemically clean piece of india-rubber containing sulphur is given in the curve ST. As the loss was very slow we could not use the auxiliary condenser, and, therefore, had to measure roughly the capacity of the arrange-

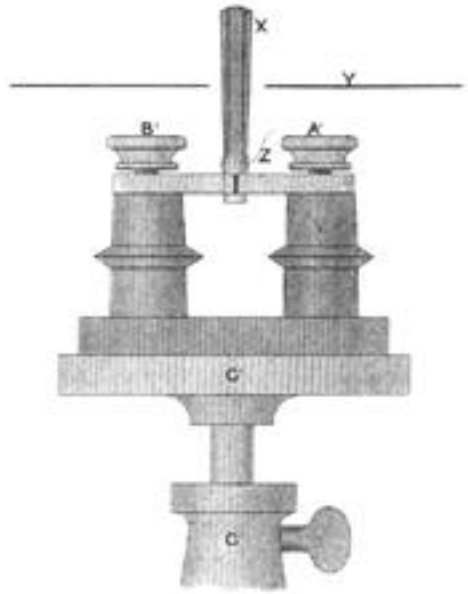
ment, which was found to be 0·000208 microfarad. The area of each of the platinum plates, between which the india-rubber was placed, was 45·6 square centims. The thickness of the india-rubber was 0·106 centim., so that the calculated specific inductive capacity was 4·8. This seems too large; but an error, if there be one, in the determination of the capacity would have made the calculated resistance too small, whereas the resistance is much higher than that hitherto obtained with any of the forms of india-rubber experimented on by electricians. We found that the capacity of the electrometer quadrants was neglectable in these, and in the ebonite observations. We give the temperature and the corresponding values of $\frac{1}{t}\log\frac{E_1}{E_2}$, and of x in megohms for the points S, a, b, c, T of the curve ST.

	Temperature.	$\frac{1}{t}\log\frac{E_1}{E_2}$	x in megohms.
S	67° C.	0·0100	5391×10^6
a	75°	0·0187	2882×10^6
b	81°·6	0·0275	1960×10^6
c	86°·7	0·0390	1382×10^6
T	90°·7	0·0531	1015×10^6

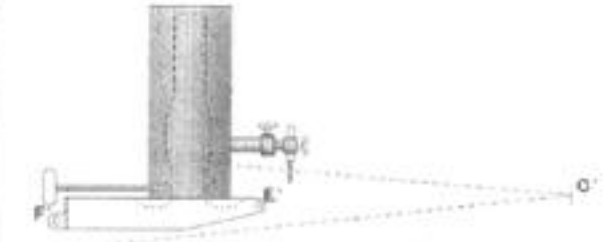
II. "On the Viscosity of Dielectrics." No. I. By W. E. Ayrton and John Perry, Professors in the Imperial College of Engineering, Tokio, Japan. Communicated by Professor Sir W. Thomson, LL.D., F.R.S. Received October 2, 1877.

It is well known that india-rubber has a greater specific resistance and a less specific inductive capacity than gutta-percha. Now a popular explanation of this might be given as follows:—Imagine a portion of the india-rubber in an india-rubber condenser replaced by a metallic or other conducting substance either in a single piece or in the form of grains scattered throughout the mass of the dielectric, then the resistance of the condenser will be diminished while its capacity will be increased. As more and more metal is introduced into the dielectric the capacity will become greater and greater, so that at last, if all the india-rubber be replaced by metal, we ought to consider such a condenser as having an extremely great capacity, although on account of the conduction it would be impossible to experimentally measure the charge. If the above consideration which of course really applies to a dielectric of heterogeneous constitution, be also applicable to different homogeneous dielectrics, then we might expect to find that for all dielectrics the specific inductive capacity diminishes as the specific resistance increases. Now the experiments we have lately been engaged on concerning specific resistances enable us to prove that in the case of several well-known dielectrics this is really so, as will be seen from the following table:—

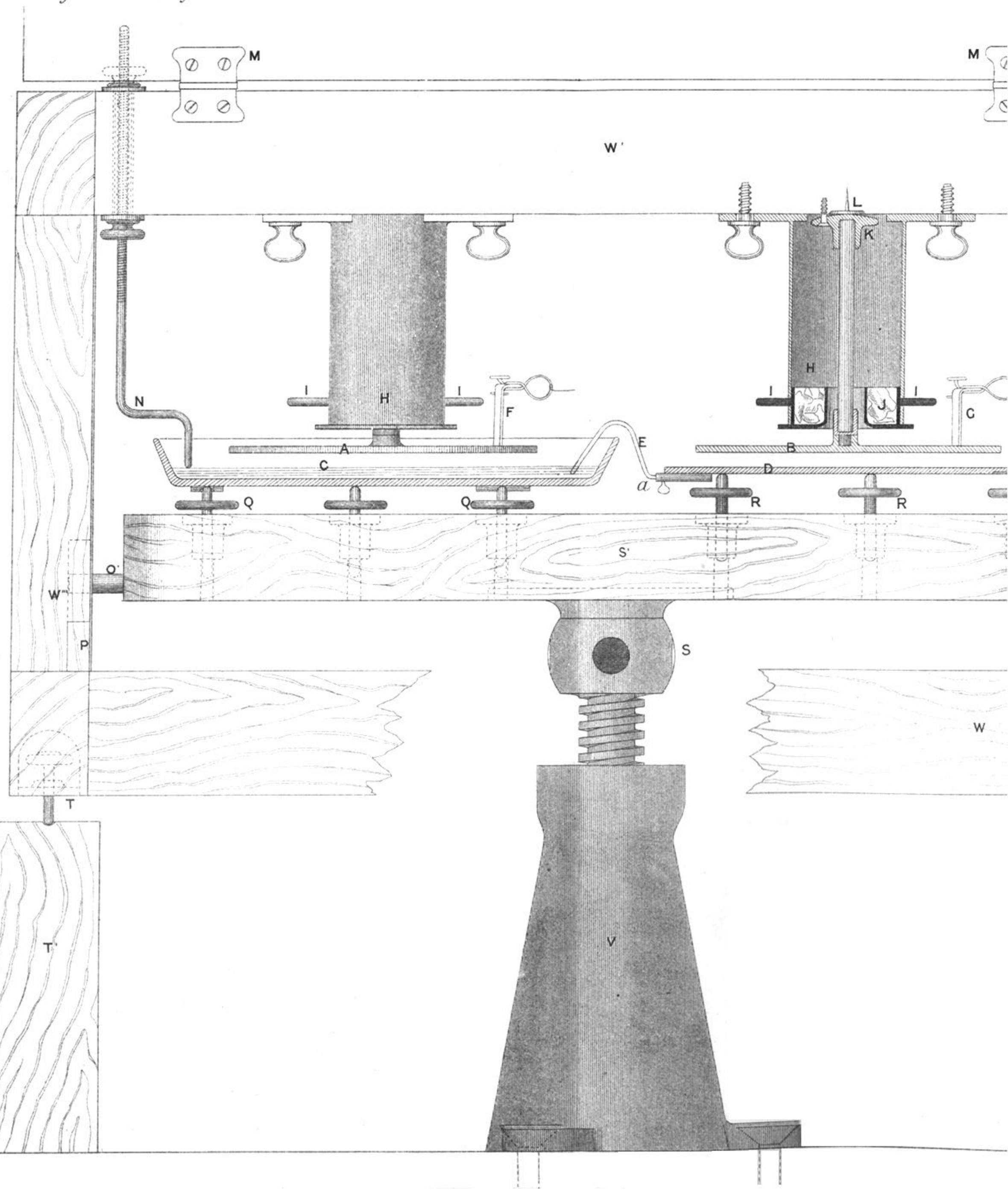




ONE FOURTH [FOR FIGURE BELOW ONE EIGHTH] OF FULL SIZE.



Ayrton & Perry.



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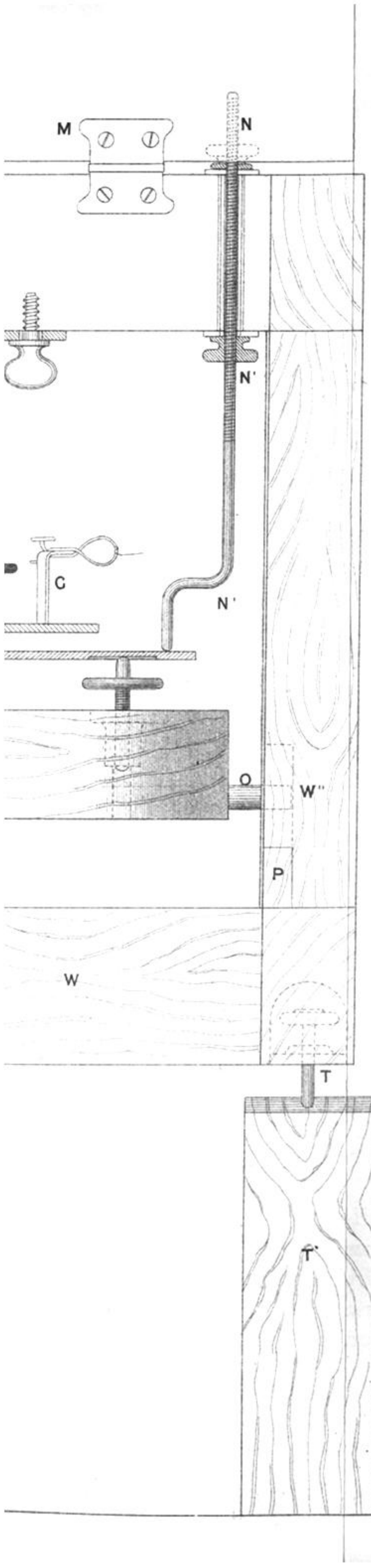
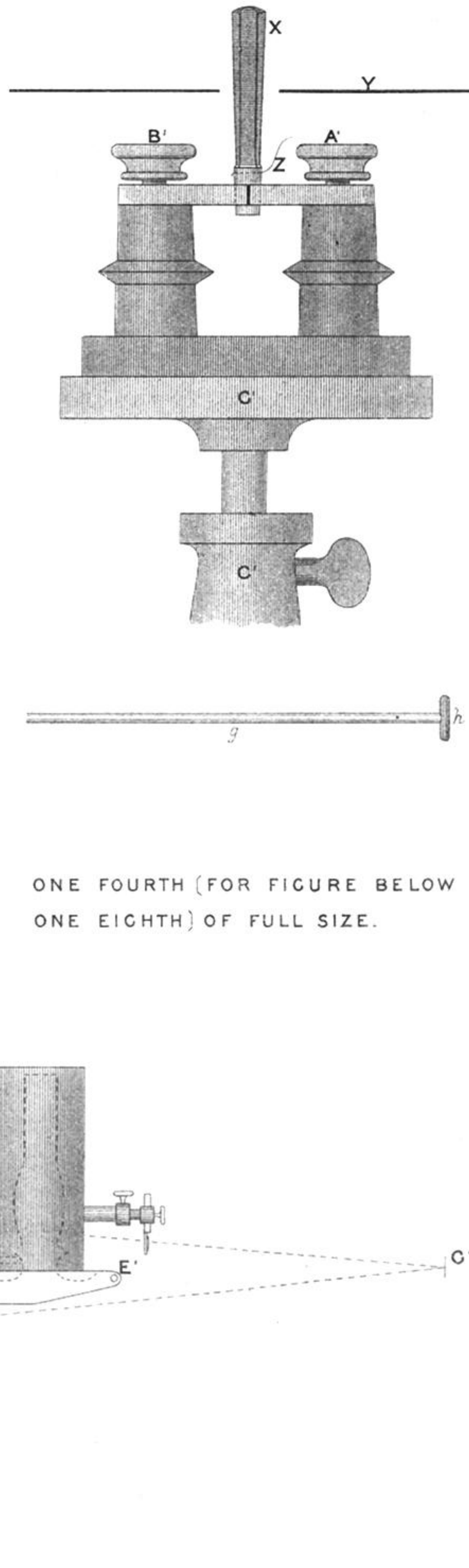
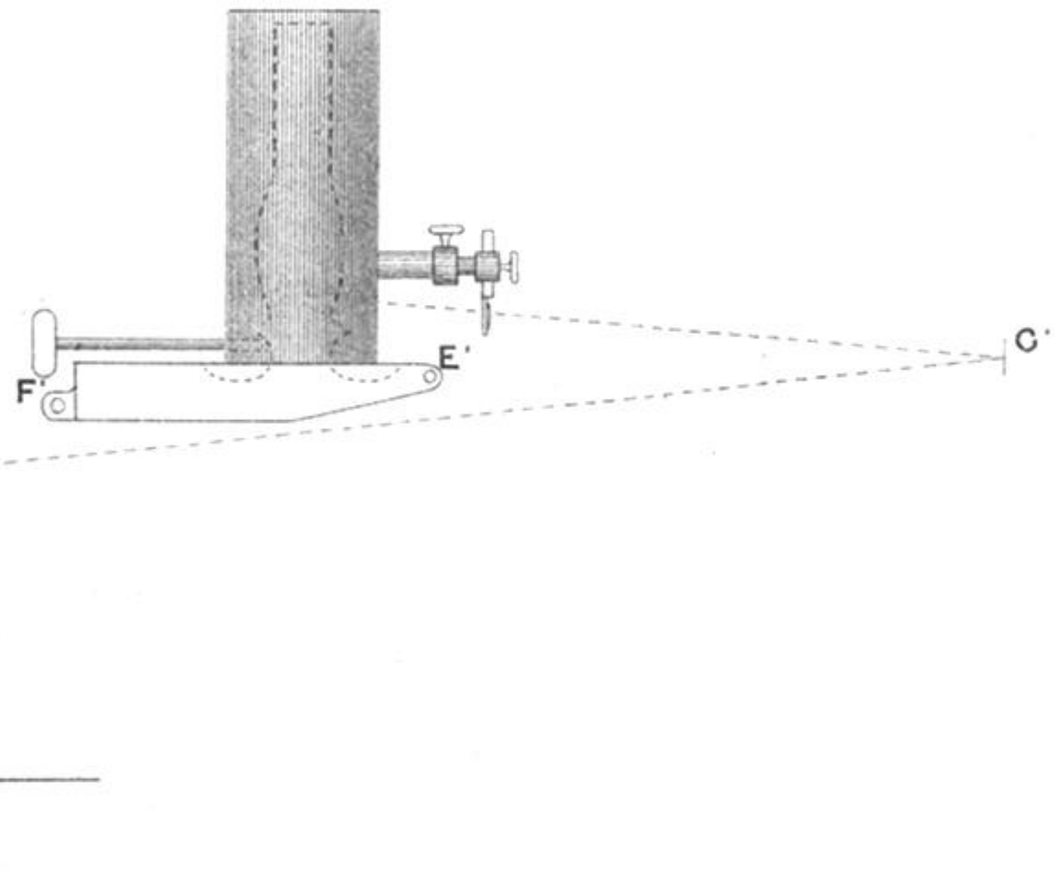




ONE FOURTH (FOR FIGURE BELOW ONE EIGHTH) OF FULL SIZE.



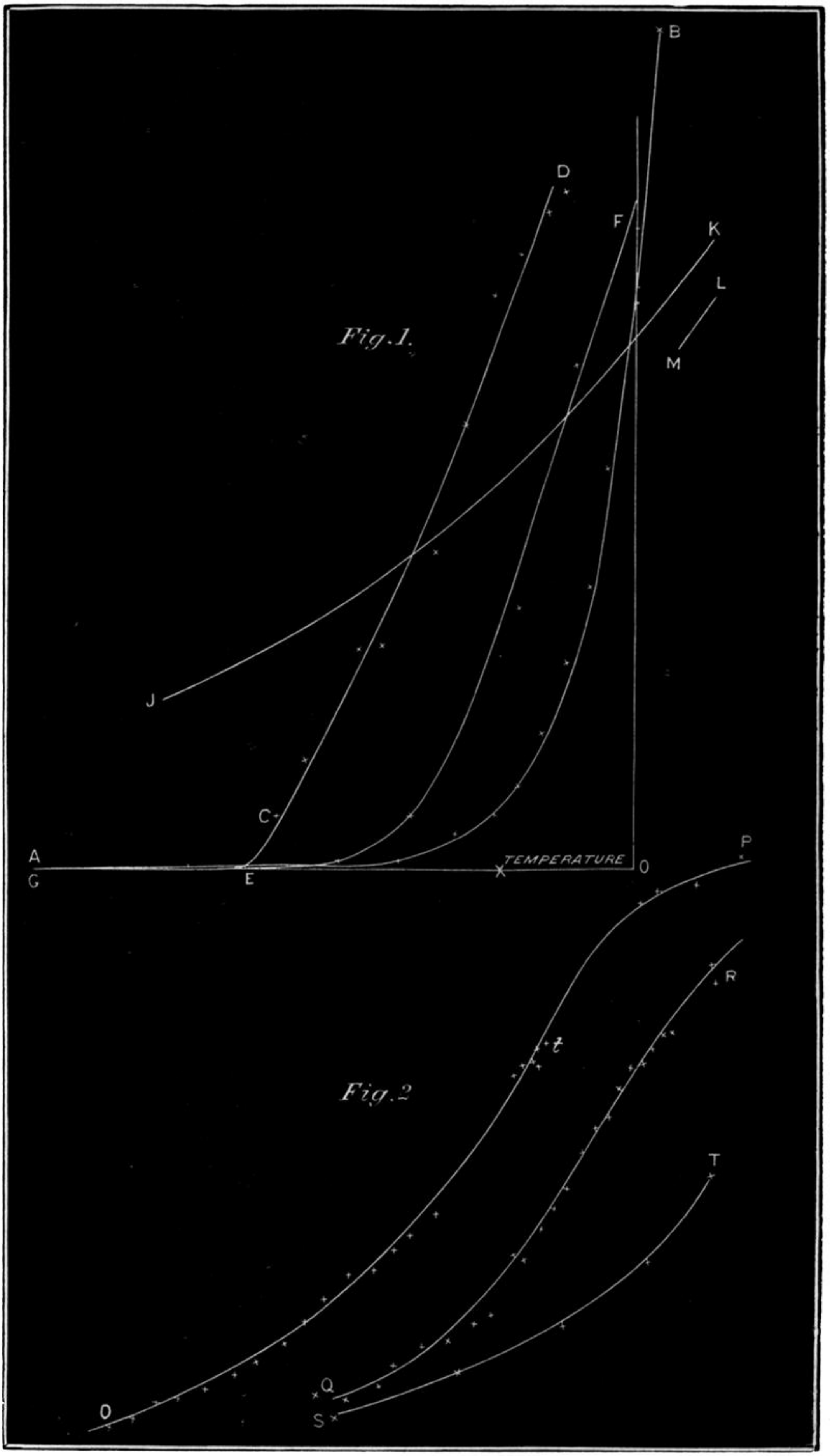


Fig. 1.

Fig. 2